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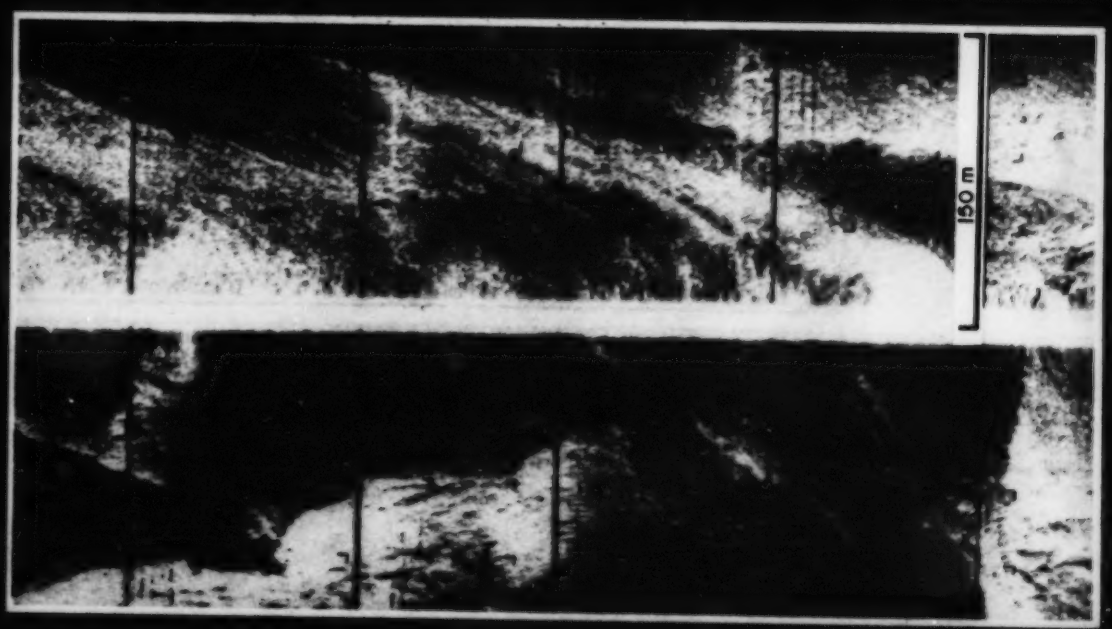

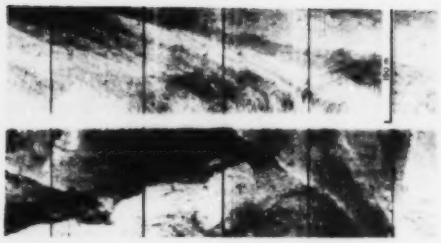

COVER

Part of a sidescan sonograph showing linear sand–shell ribbons (top) partially covering a bedrock scarp of Forteau Formation (bottom) on the eastern slope of Centre Bank South. See Map 90-6 for location of sonograph image. (Image processed by J.Y. Guigné.)

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DEPARTMENT OF MINES AND ENERGY
GOVERNMENT OF NEWFOUNDLAND AND LABRADOR

SURFICIAL AND BEDROCK GEOLOGY BENEATH THE STRAIT OF BELLE ISLE IN THE VICINITY OF A PROPOSED POWER-CABLE CROSSING

C.M.T. Woodworth-Lynas, J.Y. Guigné and E.L. King

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Senior Geologist R.F. BLACKWOOD

Editor C.P. G. PEREIRA

Copy Editor D. WALSH

Typesetting B. STRICKLAND

Word Processing D. DOWNEY
J. MATTHEWS

Supervisor, Cartographic Services K. BYRNE

Cartography D. LEONARD (Photomechanical)
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T. SEARS

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Telex: 016-4724
Fax: (709) 729-3493

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Authors' Address: *Centre for Cold Ocean Resources Engineering*
Memorial University of Newfoundland
St. John's, Newfoundland
Canada
A1B 3X5

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Position 2 is an intermediate stage (corresponding to the Belle Isle Phase of the Long Range Glaciation; Grant, *in press*) during which marine drawdown and probable calving into the Gulf of St. Lawrence have become effective. In the zone of confluence between the two ice sheets, flow is toward the reader.

Position 3 represents the time at which near-buoyant ice has retreated north to the Strait of Belle Isle region.

Position 4 represents initial lift-off on the southern side of the Strait and separation of the two ice masses.

Position 5 is the time of ribbed-moraine development in the Strait (corresponding to the Hare Bay Phase of the Long Range Glaciation; Grant, *in press*) before retreat and stabilization at the Bradore Moraine in Labrador (position 6) at approximately 12,600 years B.P. (Grant, *in press*). LT = Labrador Trough, CB = Centre Bank, NT = Newfoundland Trough..... 34

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PREFACE

This report presents results of geological, geophysical and engineering studies carried out by Newfoundland and Labrador Hydro on the feasibility of installing high-voltage direct-current (HVDC) submarine cables beneath the Strait of Belle Isle for the purpose of transmitting hydroelectric power from Labrador to the Island of Newfoundland. These studies were part of a much larger program to evaluate the potential for developing hydroelectric power at the Gull Island site on the lower Churchill River in Labrador for transmission to the Island of Newfoundland. Results of most of the work in the Strait of Belle Isle were presented in the form of contract reports to Newfoundland and Labrador Hydro between 1973 and 1984. Because the reports were, and still are, proprietary, contractors often did not know the details of previous work. As a result, many reports duplicate information, the interpretations of which differ. Others make use of past work (particularly maps) but frequently fail to cite the original source. These factors have made it hard to resolve new data from old, making geological correlation difficult. In the present work, we have attempted to resolve these problems by citing from the original documents. Also, because we have had access to all data, we have attempted to clarify the problems with geological correlation, particularly with respect to the nomenclature of bedrock units and terminology of surficial geological features.

Although we do not present new data in this report, we present new interpretations with respect to nomenclature of bedrock units and their distribution, and add to the knowledge of glacial history of the Strait based on the surficial geology and the existence of exposed suites of ribbed moraines. It has been our intention to produce a document that reviews and integrates the results of previous work, and which can be used to refer to the original more-detailed contract reports.

INTRODUCTION

LOCATION AND ACCESS

The Strait of Belle Isle is a channel located between the northwest coast of the Great Northern Peninsula of the Island of Newfoundland and the southeast coast of Labrador (Figure 1). At its narrowest point, the Strait is 17 km wide and has a maximum water depth of 120 m. It is a busy route for trans-Atlantic shipping, providing access to and from the St. Lawrence Seaway and the Great Lakes. Physiographically, the Strait is a northeastward extension of the Esquiman Channel and Mecatina Trough, terminating on the Northeast Newfoundland Shelf in the vicinity of the Bradore Marginal Trough.

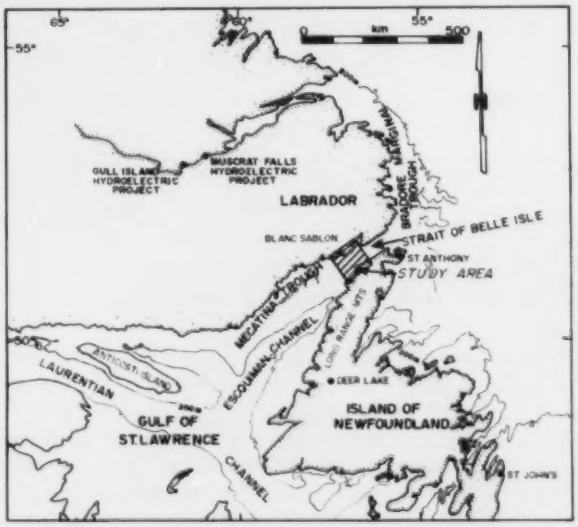

Figure 1. *Location map of the Strait of Belle Isle.*

The field season for marine work is restricted to the open-water months, generally June to December, with the most clement weather being in July and August. Sea ice, drifting from the Labrador Sea, blocks the Strait from January to May, but icebergs may be present well into summer, being driven in and out of the Strait by strong tidal currents.

DATABASE SUMMARY

Regional description of the surficial sediments was first carried out by Drapeau (1968) based on an echogram, grab-sampling, underwater video and mapping survey. He produced a surficial map of the narrowest part of the Strait on which sand, gravel, and a sand–gravel mixture are identified. Forteau Bay and L'Anse-au-Loup were mapped in more detail.

The first high-resolution profiler and sidescan sonar data collected in the area were interpreted to indicate the presence of a relatively continuous layer of undifferentiated sediments across the Strait (Nova Scotia Research Foundation, 1973). Estimates of overburden thickness ranged from <3 m up to 5 m. Where overburden does not blanket bedrock, ponded surficial deposits were shown to be separated by long, strike-parallel ridges. The ridges cover a broad area of seabed in the Newfoundland Trough and have since been shown to be more extensive (Map 90-6). In some places, these features were interpreted as fault-bounded bedrock ridges. (The ridges are important features in the Strait because of their potential effect on determining seabed cable routes.) The features have variously been interpreted as gravel- and cobble-covered bedrock ridges (Kenting Exploration Services Ltd., 1979), iceberg scours (Josenhans, 1981) and as DeGeer moraines by Guigné and King (in Beaver Dredging Company Ltd., 1981b; Shawmont Newfoundland Ltd., 1984; Lower Churchill Development Corporation, 1984b). In this report, a description of the morphology and possible genesis of the ridges are presented.

Other work included sidescan-sonar surveys from which numerous iceberg scours (now recognized as ridge features) were interpreted (Nova Scotia Research Foundation, 1974a,b). Bedforms, termed 'sand/gravel waves', were also identified from this survey in the Newfoundland Trough, on Centre Bank and locally in the Labrador Trough (Map 90-6).

Shawmont Newfoundland Ltd. (1979) reviewed much of the work on surficial geology and presented a revised surficial-geology map. This work included Drapeau's (1968) data, as well as a copy of the surficial-geology maps produced by the Nova Scotia Research Foundation (1974b).

An extensive survey by Kenting Exploration Services Ltd. (1979) confirmed the coarse (pebble, cobble, boulder) nature of the surficial sediments, and their median thickness was interpreted to be 1.5 m with isolated pockets up to 4 m. The survey results actually underestimate true thicknesses because of the poor quality of the geophysical data, which may have led to errors in interpretation. The linear ridge features were interpreted as bedrock ridges, and numerous iceberg scours were interpreted to occur in water depths from 36 m to 83 m. Bedforms, described as 'sand waves', were identified in Forteau Bay and along the steep slope of the Newfoundland Trough. An extensive marine survey was carried out in 1981 by Geonautics Ltd. under contract to the Beaver Dredging Company Ltd. (1981b, c); it was intended to define potential seabed cable-crossing routes. The work included nearshore surveys of possible cable landfall areas at Yankee Point, Pointe Amour, Forteau Bay, and Forteau Point. In addition, a widely spaced regional grid between two potential routes was surveyed. Data collected during the survey included echosounder, sidescan sonar, high-resolution deep-towed boomer seismic reflection, surface-towed boomer seismic, seabed photography and current (drogue) measurement. These data and a later survey form the bulk of the information used in compiling the surficial-geology chart produced here (Map 90-6).

Boring and sampling of overburden and bedrock at 17 localities along potential cable routes were also carried out

by the Beaver Dredging Company Ltd. (1981c) from a ship-deployed diving bell. The borehole program recovered the only sub-surface samples from the seabed of the Strait in this region. Information from the boreholes provides control for stratigraphic interpretation of the Quaternary deposits. The boreholes also provide the only bedrock samples, information from which has been used in constructing the bedrock geological cross-section. Geology maps produced from the 1981 survey by Geonautics Ltd. for the Beaver Dredging Company Ltd. (1981d) were used to plan four submersible dives on specific seabed features (Josenhans, 1981). A critical evaluation of all existing reports that describe the surficial deposits was prepared by Chagnon (1982).

A marine survey of a potential southern cable route in an area of thicker overburden and deeper water was conducted by Geonautics Ltd. for Shawmont Newfoundland Ltd. (1984). Potential landfall sites at L'Anse-au-Clair and Winter Cove were also investigated. The survey collected echogram, sidescan sonar and deep-towed boomer profiler data.

Geonautics Ltd. reviewed the marine mapping work from the narrow part of the Strait and compiled much of the existing data on surficial-geology and seabed features into one map (Lower Churchill Development Corporation, 1984b). In addition, a detailed bathymetric chart was prepared. These two maps are used as a base to present the bedrock- and surficial-geology information on charts in this report. The Lower Churchill Development Corporation (1984a) reported on an experimental cable-laying seabed-plough program carried out by ITM (Offshore) Ltd., U.K. The plough was used successfully along three potential cable routes (routes A, B and C on Maps 90-5 and 90-6).

PREVIOUS WORK

QUATERNARY GEOLOGY

The earliest Quaternary studies were carried out by Milne in 1874. He proposed a 'diluvial' origin for the surficial deposits and glacial striae of Newfoundland; the higher regions were interpreted as supporting several ice caps. Murray (1883) and Chamberlain (1895) supported the concept of local ice caps but believed that these developed after the Island of Newfoundland had been first overridden by east-flowing glaciers. DeGeer (1892) postulated the existence of a Newfoundland ice cap throughout the last glaciation based on the geometry of raised beaches. Daly (1902, 1921) added additional support to this hypothesis with observations of raised beaches around St. Anthony and in southern Labrador. Fairchild's (1918) regional work in the Gulf of St. Lawrence also led him to conclude that a Newfoundland ice cap once existed.

Coleman (1920, 1926, 1930) recognized three weathering zones in the Long Range Mountains, the degree of weathering thought to be an indicator of the duration of subaerial exposure since the zones were last glaciated. He postulated that Labrador ice never reached the Strait of Belle Isle. Tanner (1940) and MacClintock and Twenhofel (1940) also noted these weathering zones but discounted their significance as indicators of former glaciations. From his analysis of raised beaches and the marine limit, Flint (1940) suggested that Labrador ice completely covered the Island of Newfoundland during the last glaciation.

More recently, stratigraphic evidence from the Island of Newfoundland has revealed that there was more than one glacial phase, and that during the last glacial maximum, island-centred ice caps reached, but barely extended beyond, the coast (see for example Grant, 1977; Brookes, 1977a,b; Tucker and McCann, 1980). Fulton and Hodgson (1979) postulated the Late Wisconsinan ice limit lay far inland, and Rogerson (1981) indicated that most of the Strait of Belle Isle area was unglaciated. These interpretations contrast with more recent work by Mayeski *et al.* (1981), who placed the ice margin far offshore.

The most recent work in the Strait of Belle Isle region is that of Grant *(in press)*, who proposed three glacial phases:

1. The earliest phase (the St. John Zone Glaciation) was interpreted to have occurred about 500,000 to 440,000 B.P. based on a qualitative assessment of the rate of stream entrenchment. This glacial phase is correlated with oxygen isotope Stage 12, and records an expansion from the northwest of the Laurentide Ice Sheet to cover the whole area.

2. The second phase (the Doctor's Zone Glaciation) occurred about 100,000 B.P. and was assigned either to the Late Illinoian (oxygen isotope Stage 6) or early Wisconsinan. This interpretation was based on geomorphic terrain maturity and rate of stream entrenchment. The Doctor's Zone phase records the development of an independent Newfoundland ice cap, which merged with Laurentide ice. Nunataks projected through the ice in the region of the St. John Highlands on the west side of the Northern Peninsula. A period of early Wisconsinan cirque glaciation occurred after the Doctor's Zone Glaciation, when relative sea level stood about 40 m lower than at present.

3. The last phase (the Long Range Zone Glaciation) is Late Wisconsinan in age based on depth of soil formation and freshness of glacial striae. This glacial phase is interpreted to have occurred between 25,000 and 10,000 B.P. During this phase, glacier ice, centred over the Northern Peninsula, covered all of the land area of the Strait of Belle Isle except for the summits of the St. John Highlands. Six sub-

phases of the Long Range Zone Glaciation are recognized as follows:

White Hills Phase. Southeast-moving Labrador ice crossed the Strait of Belle Isle, overrode the White Hills near St. Anthony, and probably penetrated well offshore beyond St. Anthony. Ice also flowed around the north end of the Long Range Mountains and into White Bay but did not reach the Grey Islands.

Belle Isle Phase. Southeast-flowing Laurentide ice merged with north-flowing Newfoundland ice resulting in a southwestward-directed flow along the Strait of Belle Isle toward the north end of Esquiman Channel where a calving margin probably formed. The ice surface in the St. John Highlands region reached an altitude of between 300–500 m at this time.

Hare Bay Phase. Ice retreated by calving of icebergs on the Atlantic coast and in the Gulf of St. Lawrence. These two oceanic regions separated by glacial ice in the Strait of Belle Isle, are referred to as the Daly Sea and Goldthwait Sea, respectively. As Laurentide and Newfoundland ice became separated during the retreat, the Goldthwait Sea expanded eastward from the Esquiman Channel across the Coastal Lowlands toward Hare Bay. A series of 400 annual(?) DeGeer moraines developed on the lowland prior to 11,000 years B.P. (the oldest date from marine sediment) indicates that the ice margin was in direct contact with the sea at this time. Two separate ice masses existed, one centred over Hare Bay, and the other in the Long Range Mountains. Relative sea level stood about 130 m higher than at present.

Bradore–Piedmont Phase. Labrador ice, flowing nearly southward, stabilized at about 12,600 years B.P., constructing the Bradore Moraine (approximately 15 km inland and parallel to the coast) at about the marine limit. About 200 years later, southeast-flowing ice overrode the Bradore Moraine to form the Belles-Amours Moraine, which has a submarine extension in the Strait of Belle Isle. At the same time on the northwest coast of the Northern Peninsula, the large Piedmont Moraines were being formed in the River of Ponds region by Newfoundland ice from the Long Range Mountains.

Ten Mile Lake Phase. At about 11,000 years B.P., Newfoundland ice readvanced northward from the Long Range Mountains into the Goldthwait Sea, which was at a level about 80 m higher than present, and built the Ten Mile Lake and Leg Pond moraines. Laurentide ice had presumably retreated from the Belles-Amours Moraine at this time.

Cloud River Phase. Long Range ice retreated from the Ten Mile Lake Moraine, and small end moraines were constructed inland, marking the final position of the stagnating ice cap.

BEDROCK GEOLOGY

Rocks of Precambrian and Paleozoic age outcrop extensively on both sides of the Strait of Belle Isle. Although lithological and fossil descriptions existed from certain localities (e.g., Bayfield, 1845; Billings, 1865; Weston, 1895), the earliest systematic work in the region was by Richardson in 1860 (*in* Logan, 1863), who divided the Cambrian and Ordovician succession into 17 lithostratigraphic units. Seventy years later these units were redescribed by Schuchert and Dunbar (1934). Since then, significant contributions to the understanding of both local and regional geology have been made by Cooper (1937), Betz (1939), Baird (1956), Clifford and Baird (1962), Tuke (1966), Gillis (1966), Williams (1967) and Williams and Stevens (1969).

Recent geological mapping of the Newfoundland side of the Strait was carried out by the Newfoundland Department of Mines and Energy, principally by Knight (1977a, b, 1978, 1980a, b, 1983, 1985), Knight and Saltman (1980) and Knight and Boyce (1984). Bostock *et al.* (1983) provided the most recent comprehensive study of the entire region. They included detailed descriptions of boreholes drilled in 1974 and 1975 on the Labrador and Newfoundland coasts on behalf of Newfoundland and Labrador Hydro as part of their study on the feasibility of constructing a bedrock tunnel. The tunnel was to have been used for installing cables for the transmission of hydroelectric power to the Island of Newfoundland from Labrador. In their memoir, Bostock *et al.* (1983) use these data to produce a cross-section showing the distribution of Precambrian and Paleozoic bedrock beneath the Strait. Most recently, Knight and James (1987), working on the Lower Ordovician sequence, have refined the understanding of paleoenvironments and revised parts of the stratigraphy.

Published work carried out offshore is sparse. Shearer (1973) reported on seismic-reflection surveys and confirmed the gentle (1 to 2°) eastward dip of Paleozoic formations from the Gulf of St. Lawrence toward the Strait of Belle Isle. Lack of acoustic penetration of the bedrock within the Strait of Belle Isle was attributed to high reflection coefficients from boundaries between units. This problem was to plague later deep seismic-reflection surveys carried out as part of the bedrock-tunnel feasibility study by Newfoundland and Labrador Hydro. Haworth and Sanford (1976) produced a bedrock map (Figure 2) of the northern Gulf of St. Lawrence–Strait of Belle Isle area based on geophysical data and 10 rock cores. They retrieved some of these rock cores from a series of bedrock cuestas that characterizes the bathymetrically rugged area north of Esquiman Trough. From the existence of morphological lineaments offshore from St. John Island, they interpreted a series of northeast-trending faults (Figure 2). Haworth *et al.* (1976a, b) presented magnetic- and gravity-anomaly data from the Northeast Newfoundland Shelf, including a single line within the Strait of Belle Isle. Although the same corrected data were used to compile anomaly maps in the two reports, the anomalies

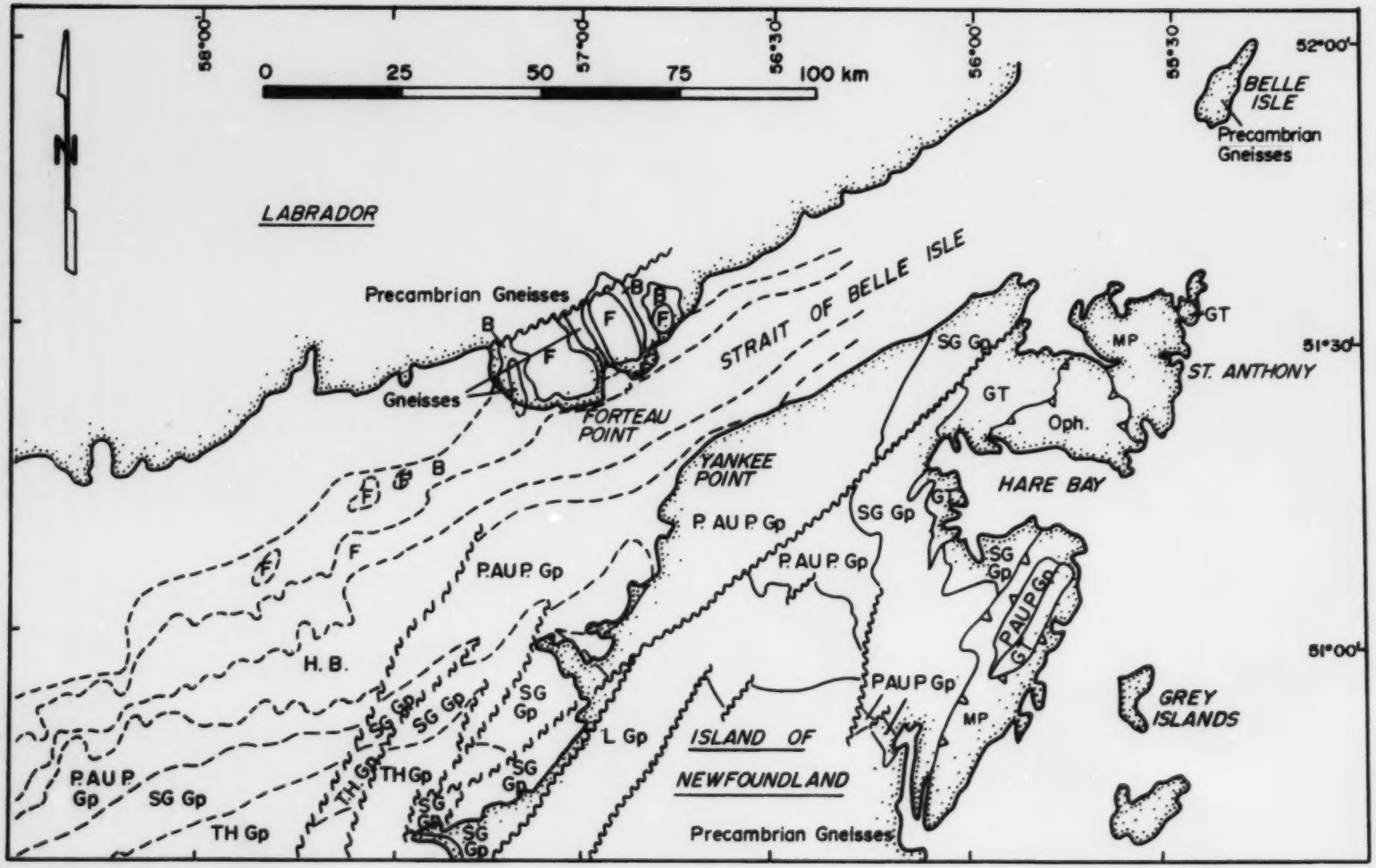

Figure 2. *General geology of the Strait of Belle Isle region (compiled from maps by Haworth and Sanford, 1976; Bostock* et al., *1983; Colman-Sadd* et al., *1989, and with advice from I. Knight, personal communication, 1990).*

LEGEND (for Figure 2)

ALLOCHTHONOUS ROCKS

Oph – St. Anthony Complex: *Ophiolitic rocks*

MP – Maiden Point Formation: *Sandstone, shale, conglomerate and mafic volcanic rocks*

AUTOCHTHONOUS ROCKS

MIDDLE ORDOVICIAN

GT – Goose Tickle Formation: *Grey siltstone, shale, slate and greywacke*

TH Gp – Table Head Group: *Grey limestone and shale*

CAMBRIAN AND LOWER ORDOVICIAN

SG Gp – St. George Group: *Grey and brown dolomite and limestone.*

P.AU P. Gp – Port au Port Group: *Grey and brown dolostone (includes March Point, Petit Jardin and Berry Head formations)*

UPPER PROTEROZOIC (?) AND CAMBRIAN

L Gp – Labrador Group (undifferentiated), includes:

H.B. – Hawke Bay Formation: *White orthoquartzite*

F – Forteau Formation: *Red to grey nodular limestone and grey shale*

B – Bradore Formation: *Red to pale-pink and maroon arkosic sandstone; minor conglomerate*

MIDDLE PROTEROZOIC (or older)

Precambrian Gneisses: *Gneiss and granitic rocks*

SYMBOLS

Geological boundary, defined

Geological boundary, approximate

Fault, defined

Fault, approximate

Thrust contact, triangles point into allochthonous rocks

shown on the maps are different, but no explanation as to why was given. The Strait of Belle Isle between Cape Norman and L'Anse-Amour is shown as a magnetic 'high' area, whereas a negative Bouguer anomaly extends out to the Bradore Marginal Trough. The authors (Haworth *et al.*, 1976a, b) offered no interpretation of these data.

BATHYMETRY

Detailed bathymetry of the study area was compiled by Geonautics Ltd. for the Lower Churchill Development Corporation (1984b). It integrates data from Canadian Hydrographic Service surveys in 1936 and 1983, a survey by Kenting Exploration Services Ltd. (1979), and two surveys by Geonautics Ltd. (Beaver Dredging Company Ltd., 1981b; Shawmont Newfoundland Ltd., 1984) (see Maps 90-5 and 90-6). Topographic features having horizontal dimensions greater than 250 m are resolved, whereas those as small as 50 m are resolved only in areas of detailed survey coverage. Five physiographic regions have been defined by Geonautics Ltd. (Lower Churchill Development Corporation, 1984c) (Map 90-5): the Labrador Coastal Zone; the Labrador Trough; Centre Bank (North and South); the Newfoundland Trough; and the Newfoundland Coastal Zone.

The Labrador Coastal Zone comprises the northwestern slope of the Labrador Trough, and extends from Pointe Amour to L'Anse-au-Clair. The zone is characterized by generally uniform slopes of between 6 and 12 percent.

The Labrador Trough is a discontinuous channel about 1 to 2 km wide that parallels the Labrador coast. It extends offshore from Ile au Bois in the south to beyond Pointe Amour in the north, reaching a maximum water depth of 115 m at the mouth of Forteau Bay.

East of Forteau Point, Centre Bank South is bounded to the north and southwest by the Labrador Trough and to the southeast by the Newfoundland Trough. It is separated from Centre Bank North by a narrow depression 85 m deep. Water depths on both parts of the Bank range from 15 to 85 m, and slopes range from 10 to 25 percent respectively.

Centre Bank North is bounded to the north and southwest by the Labrador Trough and to the south by the narrow channel separating it from Centre Bank South. The south and southeastern boundary of Centre Bank North is arbitrarily defined as the 75-m isobath, which defines approximately the break in slope of the Labrador Trough. Minimum water depth on the bank top is 50 m.

Farther to the east is the Newfoundland Trough, a broad depression 5 to 12 km wide and having water depths ranging from 70 to 125 m. Its northern margin is formed by Centre Bank, and its southern limit by a pronounced east-northeast-trending linear escarpment, up to 50 m high, which forms the northern boundary of the Newfoundland Coastal Zone. East-northeast-trending ridges and troughs 1 to 2 km long characterize the topography of the Trough in the southwest; irregular topography dominates the northern region.

The Newfoundland Coastal Zone is bounded to the southeast by the Newfoundland coast and to the north by the linear escarpment that separates it from the Newfoundland Trough. Along the crest of the escarpment, water depths reach a maximum of 70 m in the southwest and 25 m in the northeast. Seabed slopes range from 0.5 to 2 percent. In the Coastal Zone, vertical bedding scarps having relief up to 3 m are common seabed features but are not resolved by isobaths. Visual observations made during two submersible programs in 1981 and 1985 confirm the presence of bedrock scarps having relief as great as 6 m in deeper water (Josenhans, 1981; Zevenhuizen, 1986). The Coastal Zone narrows from about 12 km in the southwest to 1.5 km northeast of Yankee Point.

BEDROCK GEOLOGY

INTRODUCTION

The Strait of Belle Isle forms the northeastern part of the Anticosti Basin, a structural depression filled with over 4500 m of Ordovician and Silurian sedimentary rocks (Cumming *in* Bostock *et al.*, 1983). The Strait is underlain everywhere by gneisses of Helikian age or older. The leucocratic to melanocratic gneisses, probably mostly of sedimentary origin (Bostock *in* Bostock *et al.*, 1983), are exposed along much of the coast and interior of Labrador. Approximately 20 km inland on the Newfoundland side of the Strait, the gneisses are exposed within the Long Range Inlier, a faulted horst block (Bostock *et al.*, 1983).

The gneisses are overlain by extensive clastic and carbonate sedimentary platformal sequences that range in age from Hadrynian (?) to Middle Ordovician and have a composite thickness of about 2100 m (Bostock *et al.*, 1983). The unconformity surface between the gneisses and the overlying sedimentary rocks has a gentle, regional southeast dip of 1 to 2°, except where locally disrupted by predominantly northeast-trending faults.

Lower Cambrian volcanic, clastic and carbonate platformal rocks that overlie the Precambrian gneisses belong to the Labrador Group (Bostock *et al.*, 1983) and define, in stratigraphic sequence, the Bateau, Lighthouse Cove, Bradore, Forteau and Hawke Bay formations. Conformably overlying the Labrador Group are carbonate rocks of the Middle to Upper Cambrian March Point, Petit Jardin and Berry Head formations of the Port au Port Group, the Lower Ordovician St. George Group and the Middle Ordovician Table Head Group (Knight and Boyce, 1984). This sequence records the following evolution of development (James *et al.*, 1989):

1. a pre-platform shelf (Labrador Group) during the Lower Cambrian,
2. the development of a narrow, Mid to Upper Cambrian, high-energy platform (Port au Port Group),
3. a wide, low-energy, rimmed platform (St. George Group) during the Early Ordovician, and finally,
4. a foundered platform developed as allochthons were emplaced during the Taconic Orogeny in Mid-Ordovician times.

It is interpreted that the Labrador Group thickens in a southeast direction based on a 25.7-m increase (27 percent) in thickness of the Bradore Formation from about 96 m (in two boreholes at Pointe Amour on the Labrador coast) to 121.7 m (in a borehole at Yankee Point on the Newfoundland coast). A complete section exhibiting a thickness of 398 m is present in the borehole at Yankee Point. Rocks represented in the study area of this report include Precambrian gneisses, the Bradore, Forteau and Hawke Bay formations of the Labrador Group, and the Port au Port Group. For a thorough treatment of the history of nomenclature, lithological descriptions, stratigraphy and paleoenvironmental interpretations, the reader is referred to Bostock *et al.* (1983), James *et al.* (1989) and Knight (1977a,b).

ONLAND BOREHOLE PROGRAM

A borehole at Yankee Point (74-B-D1, Figure 3) was drilled to a depth of 398.5 m in 1974, terminating in sandstone of the Bradore Formation. In order to determine the depth of a heterolithic unconformity between the sandstone and the Precambrian gneisses, the hole was extended to 549 m in 1975, passing through the contact at 471.5 m (Teshmont Consultants Ltd. and Harrison Bradford and Associates Ltd., 1975) (Figure 4). The contact is sharply defined and dips at an angle of 70° to the core axis. The steep angle may reflect pronounced local relief of the unconformity surface. (Relief along this contact as great as 30 m is reported by Knight and Boyce (1984) from the River of Ponds area farther south.)

The unconformable contact in the two boreholes at Pointe Amour (73-B-D2, drilled in 1973 to 150 m, and 74-B-D2, drilled in 1974 to 305 m) is not well defined and is overlain by a 1.5-m-thick quartz-pebble conglomerate. Quartz-pebble conglomerate is locally the basal unit of the Bradore Formation along the western edge of the Long Range inlier (I. Knight, personal communication, Newfoundland Department of Mines and Energy, 1990), but it is not present in the borehole (74-B-D1) at Yankee Point. Below the contact in borehole 74-B-D2 (Pointe Amour), the uppermost 2 m of the Precambrian rocks consists of mafic metasedimentary rocks, possibly representing a regolith (Teshmont Consultants Ltd. and Harrison Bradford and Associates Ltd., 1975). The depth of the contact is 122 m (73-B-D2) and 121 m (74-B-D2) respectively (Harrison Bradford and Associates Ltd., 1976d). Figure 5 shows the stratigraphy in borehole 74-B-D2.

Near Yankee Point, two 99-m-deep shot holes were drilled for placing charges as part of the 1975 seismic-refraction study (Nova Scotia Research Foundation, 1975). The stratigraphies of the holes are given by Harrison Bradford and Associates Ltd. (1976a). Marker horizons within the March Point and Petit Jardin formations correlate with similar horizons in the Yankee Point borehole (74-B-D1). A vertical offset of 53.5 m across local intraformational northeast-trending faults, mapped by Harrison Bradford and Associates Ltd. (1976b), between Yankee Point and shot hole 'A' (5.1 km to the southwest) can be inferred (Figure 6).

The depth of the contact between the Forteau and Bradore formations at Pointe Amour varies appreciably over a few hundred metres laterally. The logs from six water wells approximately 700 m northeast of the two boreholes (73-B-D2 and 74-B-D2) indicate a difference in elevation of the contact as great as 11.3 m between wells 300 m apart (Harrison Bradford and Associates Ltd., 1976b). Because no faults are indicated on the detailed map by Harrison Bradford and Associates Ltd. (1976b), these changes may reflect topographic variation at the contact.

OFFSHORE GEOPHYSICAL SURVEYS

Two seismic-reflection surveys were carried out by the Nova Scotia Research Foundation (1973; 1974a,b) in 1973 and 1974. A 400- to 600-Joule sparker system was used during the 1973 survey, which consisted of five lines run along the proposed tunnel routes. Up to sixteen reflectors were identified and correlated with the stratigraphy from the boreholes at Pointe Amour and Yankee Point (Figure 7). No faults were shown on the interpreted cross-sections. The same sparker system was used for the 1974 survey, during which three lines were run along the proposed tunnel routes. Faults were interpreted from data collected during this survey.

Re-analysis of the data from the above surveys has shown that ringing and the interference of multiples would completely mask any reflectors that may be present. Therefore, the data and results from these surveys are excluded from the interpretations presented in this report.

In 1975, eight seismic-reflection lines were run between Yankee Point and Pointe Amour using a 20-kJ sparker source and short hydrophone streamer (Geoterrex and CGG, 1975). The quality of data collected during this survey was very poor, even after filtering and stacking. The processed sections indicate little or no seabed penetration, and seabed multiples mask internal reflectors. A cross-section produced from these data shows 14 faults offsetting the Precambrian–Bradore Formation contact, with throws as great as 60 m near Pointe Amour (Figure 8). This interpretation is considered unjustified based on the re-assessment of these data by this study; therefore, the data analysis by Geoterrex and CGG (1975) is excluded from this compilation.

Results of an onland seismic-refraction experiment in 1975 to detect the Precambrian–Bradore Formation contact showed that this technique was unsuitable for an offshore survey (Nova Scotia Research Foundation, 1975). Inadequate knowledge of the seismic velocities of the Precambrian and Paleozoic rocks made data interpretation difficult. However, velocity logging was carried out in the Yankee Point borehole to a depth of 213 m (Figure 9). Mean velocities are 6,165 m/s for the Petit Jardin and March Point formations, and 4,288 m/s for the Hawke Bay Formation. A low-velocity zone having values of 3,836 and 3,931 m/s between 92 m and 152 m in the Hawke Bay Formation correlates with alternating sandstone and shale intercalations (Bostock *et al.*, 1983).

OFFSHORE DRILLING PROGRAM

An offshore drilling program to delineate the bedrock geology was initiated in 1974, but no core was retrieved during the one month of activity due to severe storms, strong currents and technical failures (Teshmont Consultants Ltd., 1976). In 1981, 22 boreholes at 17 stations were drilled from a pressurized diving bell lowered to the seabed. These holes were located along two potential routes for rock-trench-protected power cables, and, as such, deep borings were unnecessary. Sixteen holes encountered bedrock from which samples were retrieved. The maximum-drilled depth of bedrock was 3.69 m and the average depth was 2.5 m (Beaver Dredging Company Ltd., 1981a). Stratigraphic interpretations of the borehole cores were made by SNC–Lavalin (1982b), who correlated distinctive pink-orange bioturbated layers

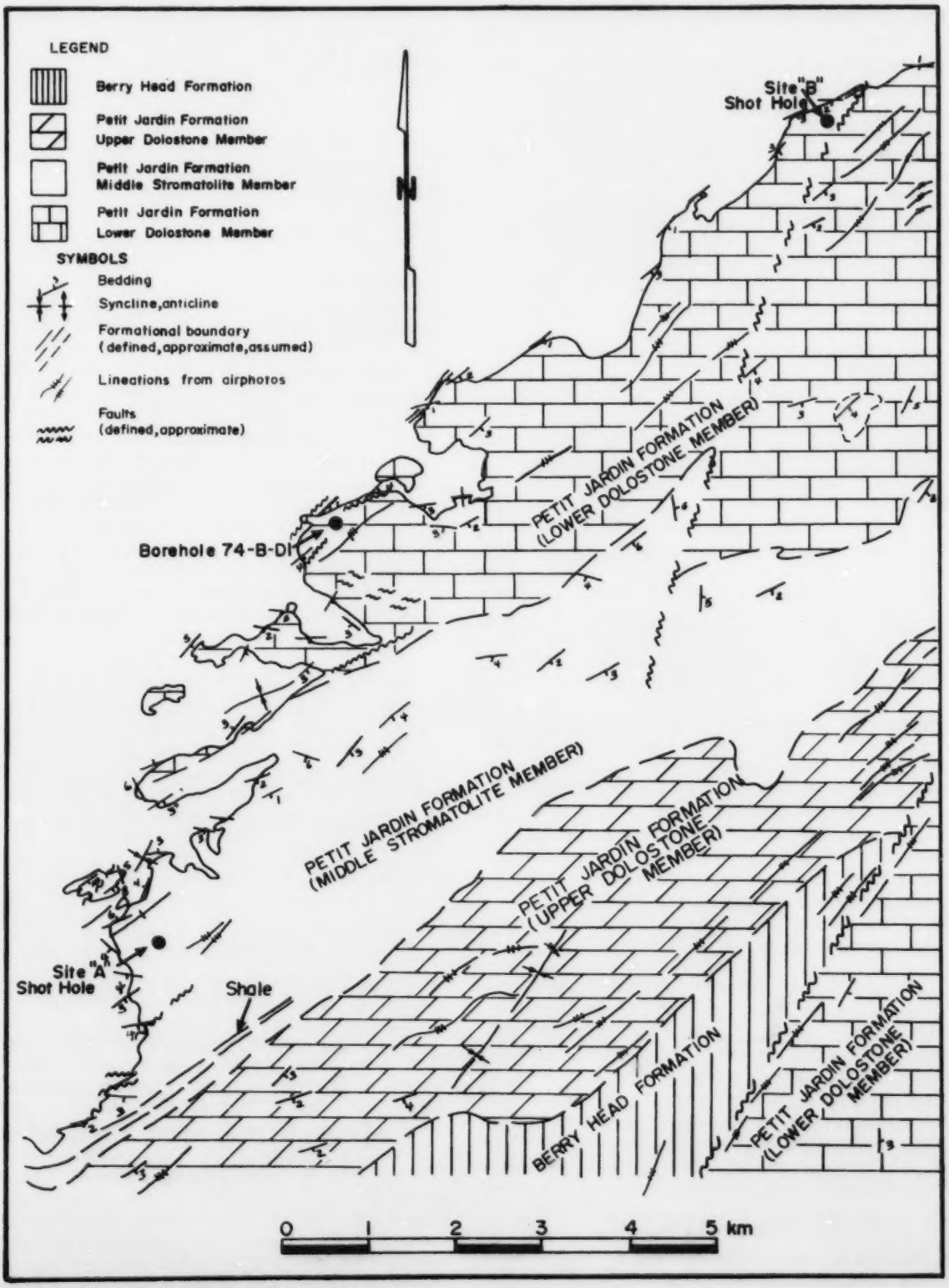

Figure 3. *Location of Yankee Point borehole (74-B-D1) and shot holes A and B on the Newfoundland side of the Strait of Belle Isle (from Nova Scotia Research Foundation, 1975). Geology from Knight (1985). Faults at Yankee Point mapped by Harrison Bradford and Associates Ltd. (1976b).*

within the Forteau Formation, found in all three onland boreholes, with similar rock types in two (A3/17 and A4/7c) offshore cores (Map 90-5). These cores represent the only samples retrieved from bedrock exposed at, or close to, the seabed in the Strait, and are the principal data source for production of the bedrock-geology map (Map 90-5).

In this report, the presence of only one fault is interpreted on the cross-section (Map 90-5), and this is an offshore extrapolation of the fault at Fox Cove, Pointe Amour, mapped by Teshmont Consultants Ltd. (1975), Harrison Bradford and Associates Ltd. (1976b) and Bostock *et al.* (1983). Anomalous northwesterly dips of up to 17° within the lower Forteau Formation occur along the coast between Fox Cove and Pointe Amour and may be possibly related to the offshore extension of the fault. The Teshmont Consultants Ltd. (1975) estimation of a vertical throw of between 26 to 27.5 m agrees well with this interpretation (see Map 90-5).

ENGINEERING GEOLOGY

INTRODUCTION

With the possibility of hydroelectric power being developed on the lower Churchill River in Labrador, the problem of a physical transmission link across the Strait of Belle Isle to the Island of Newfoundland had to be solved. Newfoundland and Labrador Hydro considered three possible methods (SNC–Lavalin, 1982a), which were:

1. installing power cables in a bedrock tunnel beneath the Strait,
2. laying cables in trenches on the seabed,
3. placing the cables on the seafloor between two bedrock adits extending from shore to the 85-m isobath (Figure 10).

All three cable-laying options were assessed by Newfoundland and Labrador Hydro. Although a power link has yet to be established, it is felt that a general description of the engineering studies that were carried out is both of interest and relevance, and places in context the effort expended in collecting geological data. This section of the report describes the different engineering problems that had to be dealt with, and how those problems are to be overcome.

TUNNEL OPTION

Initial work was carried out on the feasibility of excavating an 18.28-km-long bedrock tunnel beneath the narrowest portion of the Strait, between Pointe Amour, Labrador, and Yankee Point, Newfoundland (Patrick Harrison & Co. Ltd., 1973a). Tunnelling, although expensive when compared to laying cable on the seabed, avoids the potential for cable damage by iceberg scouring in deep water, sea-ice scouring and abrasion in shallow waters near the landing areas, disruption by bottom currents and sediment transport, corrosion, and damage by fishing gear and anchors. The tunnel option required knowledge of both subsurface geology and the engineering properties of the bedrock. On this premise, deep seismic-reflection surveys were carried out in an attempt to delineate the subsurface geology and correlate it with the known stratigraphy and engineering properties of similar rock recovered from the boreholes at Yankee Point and Pointe Amour. This was to have been followed up by an offshore drilling program to both groundtruth the geophysical interpretations, and to provide additional rock samples for engineering tests so that an effective tunnelling strategy could be developed. Patrick Harrison & Co. Ltd. (1973a) proposed driving a tunnel at a maximum depth below sea level of 177 m, with dimensions of 4.25 m in width and 5 m in height. For construction time, they forecast an average daily advance of the tunnel face, using drilling and blasting techniques, of 15.25 m, resulting in completion after 39 months. This proposal followed a more ambitious one by Fenco Ltd. (1966), who proposed a combined cable and railway tunnel, with diesel-powered shuttle passenger trains being used to transport up to 4,800 cars and trucks per day between Labrador and Newfoundland.

The bedrock tunnel was to have been advanced from the bottom of two vertical shafts, at Pointe Amour and Yankee Point respectively. Grouting of the rock around the two shaft sites was considered necessary to prevent groundwater seepage into the shafts as they were excavated. This was to be accomplished by drilling a circular pattern of holes around the shafts and pumping grout under pressure into each hole to seal off pore spaces. Grouting would be necessary down to the contact between the Bradore Formation and the Precambrian gneisses at 472 m at Yankee Point, and to 5 m below the contact at 128 m, at Pointe Amour (Harrison Bradford and Associates Ltd., 1975). The elevation level of the proposed tunnel had at this time been increased to a depth of 518 m below sea level, and later increased to 580 m so that it would be entirely within Precambrian gneisses. This was considered necessary to avoid possible problems with water seepage beneath the Strait, and to avoid impact on marine life caused by rock blasting (Newfoundland and Labrador Hydro, 1978). Construction of the vertical shafts at both Pointe Amour and Yankee Point was begun in 1975, but was suspended in 1976 when the hydroelectric Gull Island Project on the lower Churchill River was cancelled.

TRENCHES OPTION

Installing cables in seafloor bedrock trenches (Lower Churchill Development, 1980; Green *et al.*, 1982) (Figure 11) involves the removal of overburden, levelling of bedding scarps by blasting, rock trenching to a depth of 1.5 m, and cable laying. This technique requires knowledge of both bedrock and overburden properties in order to assess the kinds of equipment needed for each phase.

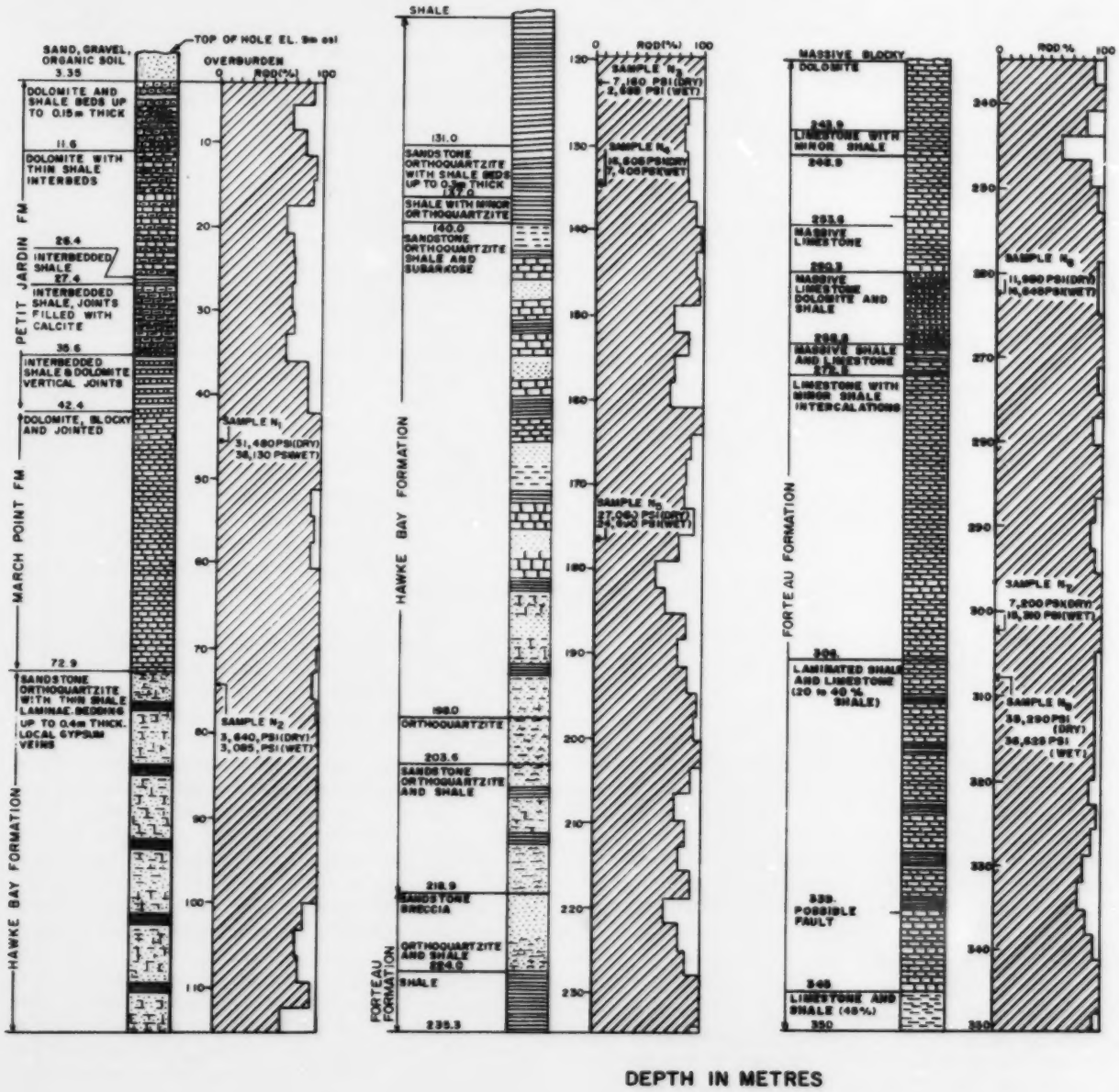

Figure 4. *Downhole stratigraphy and Rock Quality Designation (RQD) for the Yankee Point borehole (74-B-D1) (from Harrison Bradford and Associates Ltd., 1976d)*

$$RQD = \frac{\text{sum of whole core pieces } >10 \text{ cm X } 100\%}{\text{total length of core section}}$$

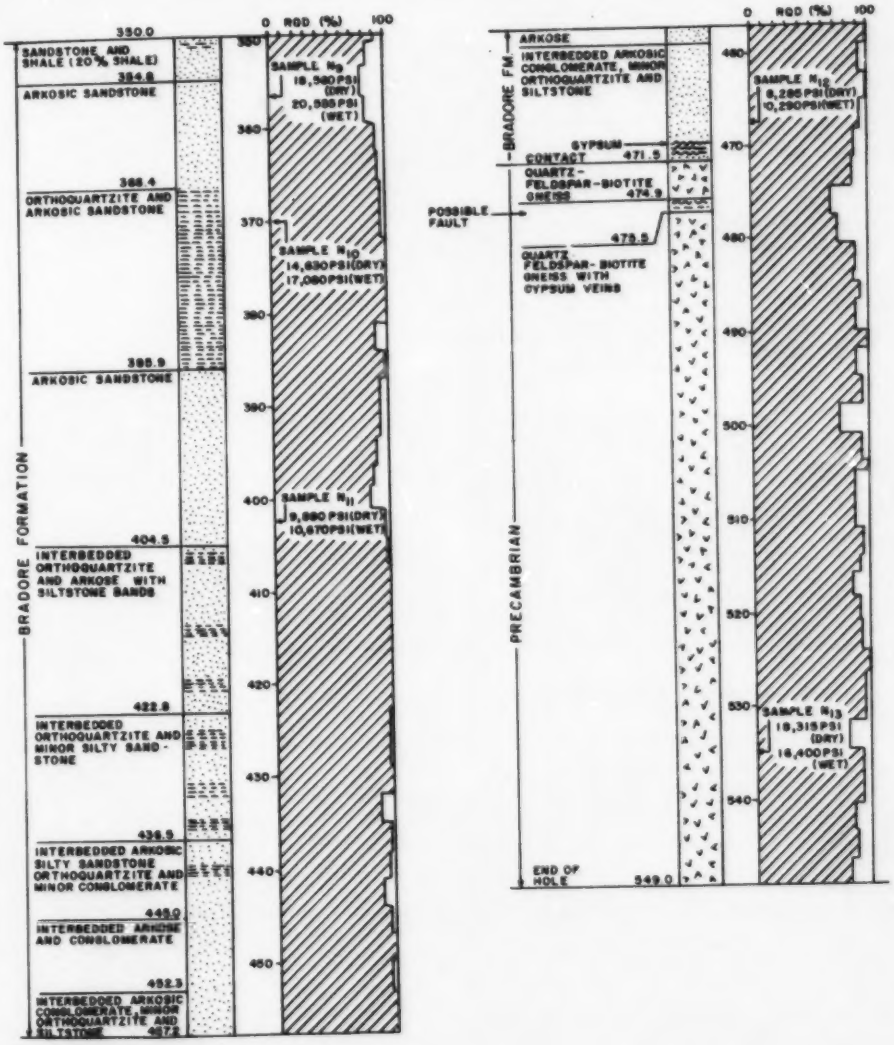

Figure 4. *Continued.*

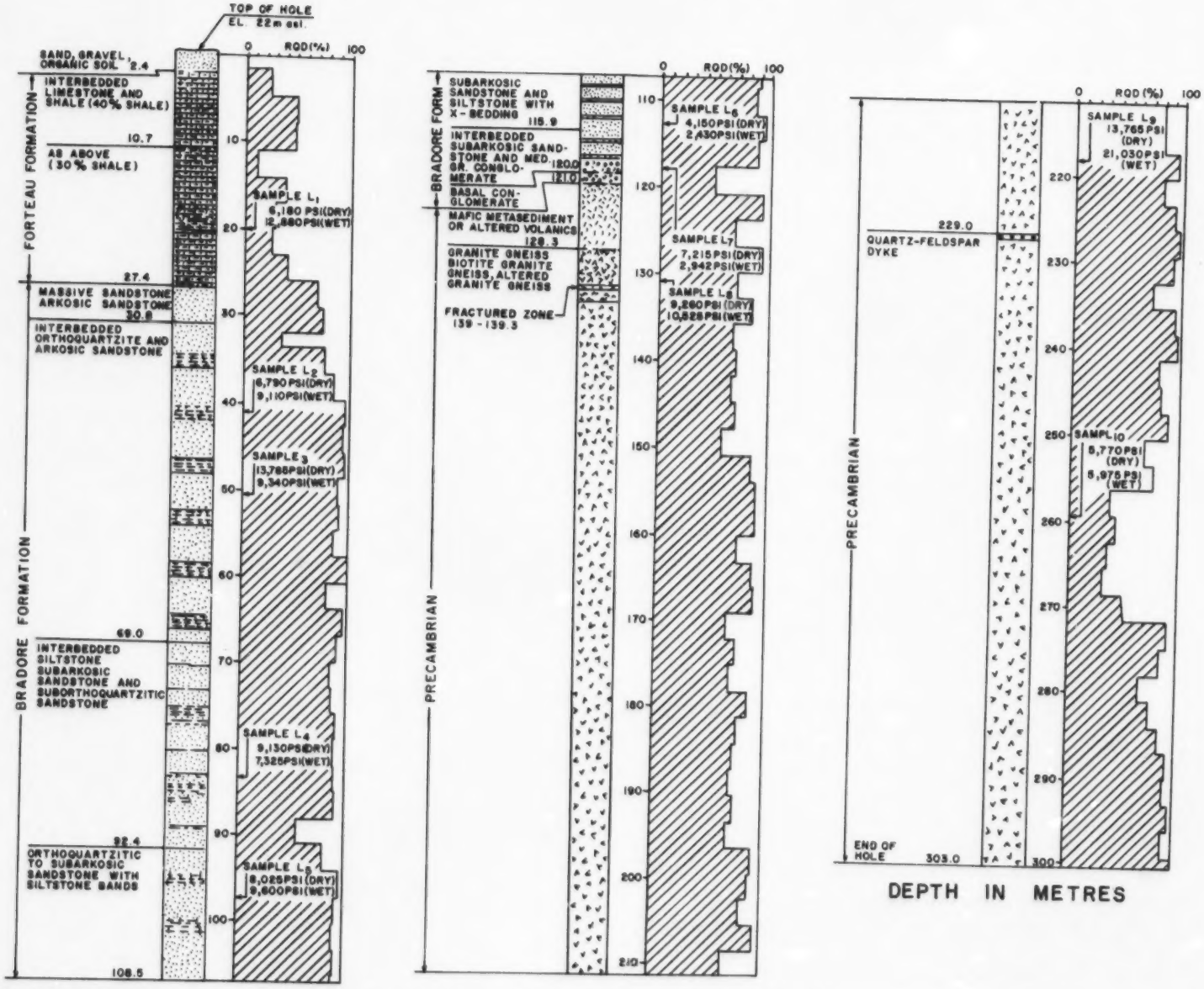

Figure 5. *Downhole stratigraphy and Rock Quality Designation (RQD) for the Pointe Amour borehole 74-B-D2 (from Harrison Bradford and Associates Ltd., 1976d)*

$$RQD = \frac{\text{sum of whole core pieces} > 10\text{ cm}}{\text{total length of core section}} \times 100\%$$

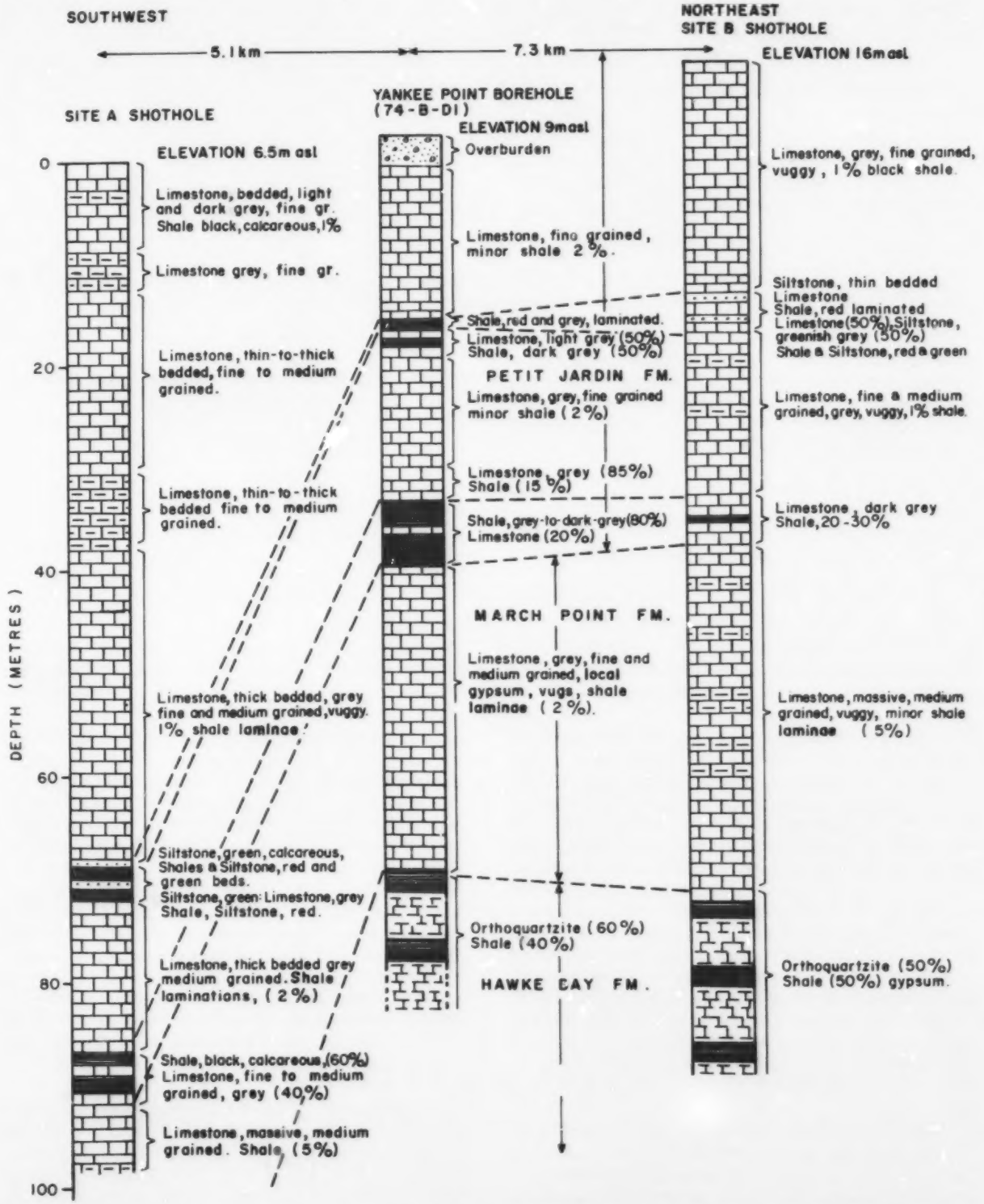
SOUTHWEST
5.1 km
7.3 km
NORTHEAST
SITE B SHOTHOLE
ELEVATION 16m asl
SITE A SHOTHOLE
ELEVATION 6.5m asl
YANKEE POINT BOREHOLE
(74-B-D1)
ELEVATION 9masl
DEPTH (METRES)
0
20
40
60
80
100
Overburden
Limestone, bedded, light and dark grey, fine gr. Shale black, calcareous, 1%
Limestone grey, fine gr.
Limestone, thin-to-thick bedded, fine to medium grained.
Limestone, thin-to-thick bedded fine to medium grained.
Limestone, thick bedded, grey fine and medium grained, vuggy. 1% shale laminae
Siltstone, green, calcareous, Shales & Siltstone, red and green beds.
Siltstone, green: Limestone, grey Shale, Siltstone, red.
Limestone, thick bedded grey medium grained. Shale laminations, (2%)
Shale, black, calcareous, (60%) Limestone, fine to medium grained, grey (40%)
Limestone, massive, medium grained. Shale (5%)
Limestone, fine grained, minor shale 2%.
Shale, red and grey, laminated.
Limestone, light grey (50%) Shale, dark grey (50%)
PETIT JARDIN FM.
Limestone, grey, fine grained minor shale (2%)
Limestone, grey (85%) Shale (15%)
Shale, grey-to-dark-grey (80%) Limestone (20%)
MARCH POINT FM.
Limestone, grey, fine and medium grained, local gypsum, vugs, shale laminae (2%).
Orthoquartzite (60%) Shale (40%)
HAWKE BAY FM.
Limestone, grey, fine grained, vuggy, 1% black shale.
Siltstone, thin bedded Limestone
Shale, red laminated Limestone (50%), Siltstone, greenish grey (50%) Shale & Siltstone, red & green
Limestone, fine & medium grained, grey, vuggy, 1% shale.
Limestone, dark grey Shale, 20-30%
Limestone, massive, medium grained, vuggy, minor shale laminae (5%)
Orthoquartzite (50%) Shale (50%) gypsum.

Figure 6. *Stratigraphy and correlations between shot holes A and B and part of Yankee Point borehole (74-B-D1) (see Figure 3 for location). Adapted from Harrison Bradford and Associates Ltd. (1976a).*

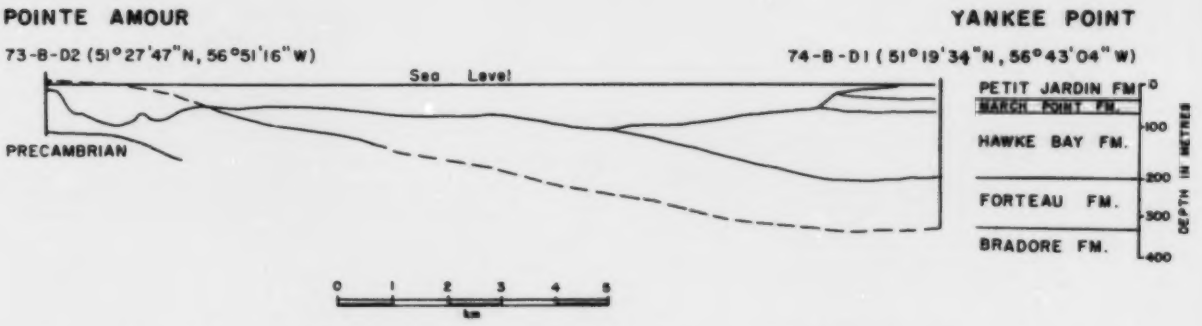

Figure 7. *Bedrock geology of the Strait of Belle Isle between Pointe Amour and Yankee Point (adapted from Nova Scotia Research Foundation, 1974a, b). Borehole positions are from Ruffman (1981).*

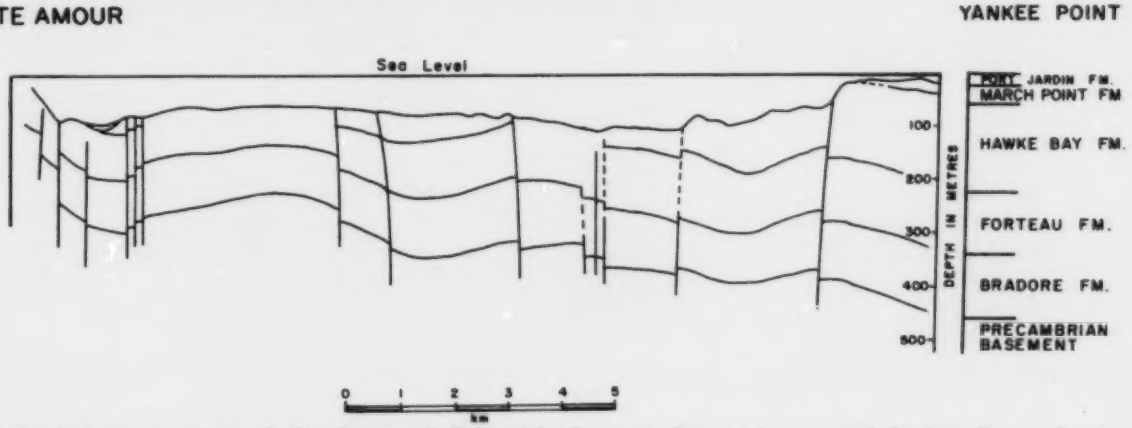

Figure 8. *Bedrock geology of the Strait of Belle Isle between Pointe Amour and Yankee Point showing interpreted faults (adapted from Geoterrex and CGG, 1975).*

Rock tests were performed on samples from the Yankee Point borehole (74-B-D1) and one of the Pointe Amour boreholes (74-B-D2), and on cores from the offshore boreholes, in order to understand properties of the bedrock formations exposed at or below the seabed in the Strait. The test results are summarized by SNC–Lavalin (1982b) and are reproduced in Appendix A. A Rock Quality Designation (RQD) is given by Harrison Bradford and Associates Ltd. (1976d) for both boreholes (Figures 4 and 5). RQD is a measure of rock 'soundness', given in percent, based on the number of fractures in a section of core. An RQD of 80 to 90 percent is considered 'good' (Teshmont Consultants Ltd. and Harrison Bradford and Associates Ltd., 1975). Geotechnical analyses were performed on soils retrieved during the 1981 offshore borehole program. The results of these tests are given by SNC–Lavalin (1982b) and are reproduced in Appendix B.

The cost of bedrock trenching is high and includes the expense of developing and constructing special equipment for the work. The cost of burying cables within overburden is less costly, and can be done using conventional ploughing methods (Lower Churchill Development Corporation, 1984a–d). There are two prerequisites for a trenched cable route. First, there must be sufficient overburden thickness to allow deep (2 m) burial for protection against ice scouring and wave action in the nearshore areas to the 12-m isobath, and to offer shallow (60 cm) burial protection against bottom fishing activities in water depths greater than 12 m. Secondly, it must be possible to use bathymetric sheltering to mitigate the risk of damage by iceberg scouring in deep water.

Geonautics (*in* Lower Churchill Development Corporation, 1984b) interpreted the existence of a buried bedrock channel system extending westward offshore from Winter Cove to the 30-m isobath (see Map 90-6). The main channel, partially filled with sediments, offers a potential nearshore route for bringing buried transmission cables to shore. A buried bedrock channel also exists in the approaches to L'Anse-au-Clair, and offers similar burial protection for a cable route in the nearshore area.

Approximately 72 km of test ploughing was carried out in August 1984. Three potential cable routes were successfully completed at an average ploughing rate of 0.9 km/h between Forteau Point and Yankee Point (route A, approximately 24 km), L'Anse-au-Clair and Yankee Point (route B, approximately 38 km), and L'Anse-au-Clair and Winter Cove (route C, approximately 36 km) (Lower Churchill Development Corporation, 1984a) (see Map 90-5 and Map

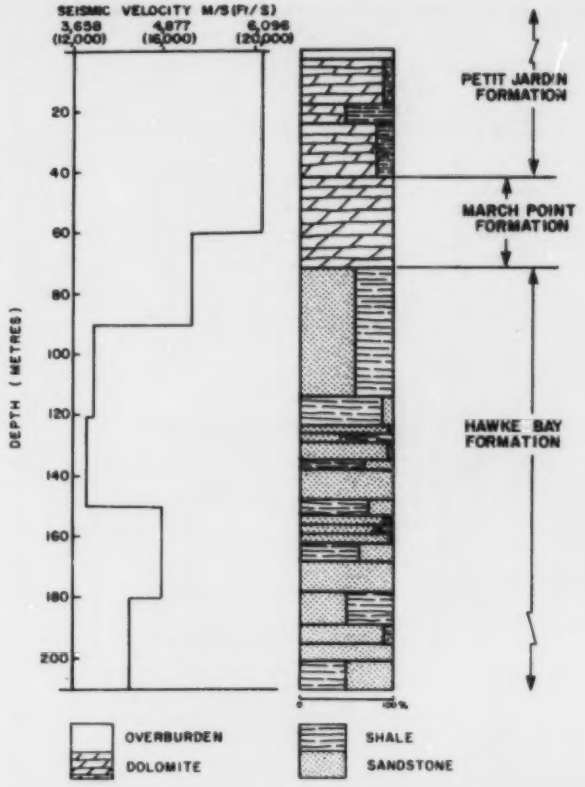

Figure 9. *Seismic-velocity profile of the upper 213 m of the Yankee Point borehole (74-B-D1). (The hydrophone became jammed in the borehole at this depth precluding further measurements.) Velocities averaged over 30-m intervals (adapted from Nova Scotia Research Foundation, 1975).*

90-6). Ploughshare penetrations of between 50 to 70 cm were achieved along 81 percent of the route between Winter Cove and L'Anse-au-Clair, along 93 percent of the route between Yankee Point and L'Anse-au-Clair, and along 82 percent of the route between Yankee Point and Forteau Point. A 5-tonne plough (Figure 12) was instrumented to allow measurement of ploughshare depth penetration, using an echo sounder. As well, audio (noise of plough during the test), video, forward-scanning sonar (for obstacle avoidance), towing tension and inclinometer data were recorded. A cable-laying plough, weighing approximately 20 tonnes, was considered capable of penetrating to at least 60 cm along the entire length of the three proposed routes (Lower Churchill Development Corporation, 1984a). The preferred route was chosen between L'Anse-au-Clair and Winter Cove (route C).

TUNNELLING–SEABED OPTION

The combination of laying power cables on the seafloor between tunnels at either terminus required a double tunnel on each side of the Strait (Patrick Harrison & Co. Ltd., 1973b). The tunnels would be 970 m and 2712 m long at the Labrador and Newfoundland termini respectively (Patrick Harrison & Co. Ltd., 1973b). The smaller of the two tunnels at 2.5 by 2.5 m would be used for fresh-air ventilation and the larger at 2.75 by 3 m would be used as a haulage way for removing material blasted from the working faces, and for discharging foul air (Figure 10a). Tunnelling would cease when the face was about 3 m below the seabed, and a final charge would be used to break up the rock. Carefully installed pipe thimbles, with stuffing boxes to prevent seepage, would permit flush joint pipe to be pushed through the broken rock to the seabed. Divers in the Strait could then thread the power cable into the pipe to be drawn into the tunnel (Patrick Harrison & Co. Ltd., 1973b). Alternatively, tunnelling may cease at about 20 m below seabed, and connection with the seabed would be made using standard pressurized drilling-and-casing techniques (Figure 10b) (SNC–Lavalin, 1982a).

SEISMICITY

Shocks from earthquakes in eastern Canada recorded between 1900 and 1978 would have produced estimated horizontal ground accelerations in the Strait of Belle Isle of no greater than 1 g (10 cm/s²) with a probability of exceedence of 0.01 per annum (SNC–Lavalin, 1980a). However, it should be noted that prior to the early 1960s the nearest seismograph stations were 1,000 km away, and would barely detect earthquakes smaller than magnitude 5 (Richter scale). Additionally, earthquakes of less than magnitude 6 would have had a location uncertainty of 50 to 100 km. Figure 13 shows the distribution of 488 earthquake epicentres in eastern Canada, of which 27 may have been felt in the region of the Strait. Earthquakes of magnitude 7 and greater have occurred more than 600 km away from the Strait. The closest event was a magnitude 3.4, which occurred on December 2, 1967, 151 km to the northwest. The recommended design maximum acceleration for bedrock-founded structures in the region is 10 cm/s² (SNC–Lavalin, 1980a).

SURFICIAL GEOLOGY

GLACIAL DRIFT

In this section, surficial geological units are described and interpreted. Much of the descriptions are based on seismostratigraphy because there are relatively few bottom samples and cores, except those from the proposed cable routes, on which to base lithological descriptions. It should be pointed out that the offshore boreholes were drilled primarily to verify the thickness of surficial units as derived from seismic profile data. Consequently, there was less emphasis on rigorous lithological description, and those in this report are commonly based on very general descriptions contained in contract reports.

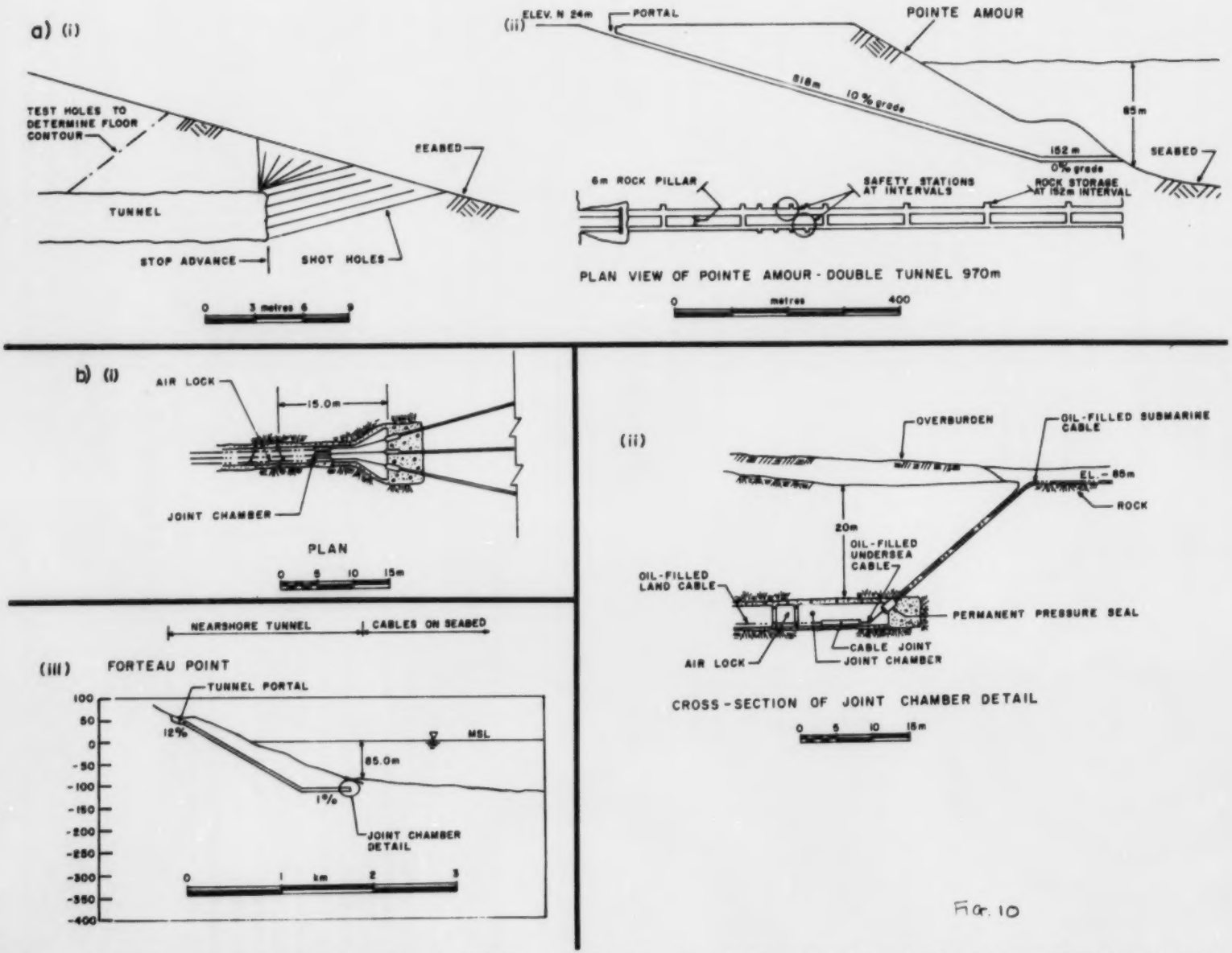

Figure 10. *Two possible schemes (a and b) for connecting HVDC power cables from the seabed to a bedrock tunnel at Pointe Amour (Patrick Harrison & Co.*

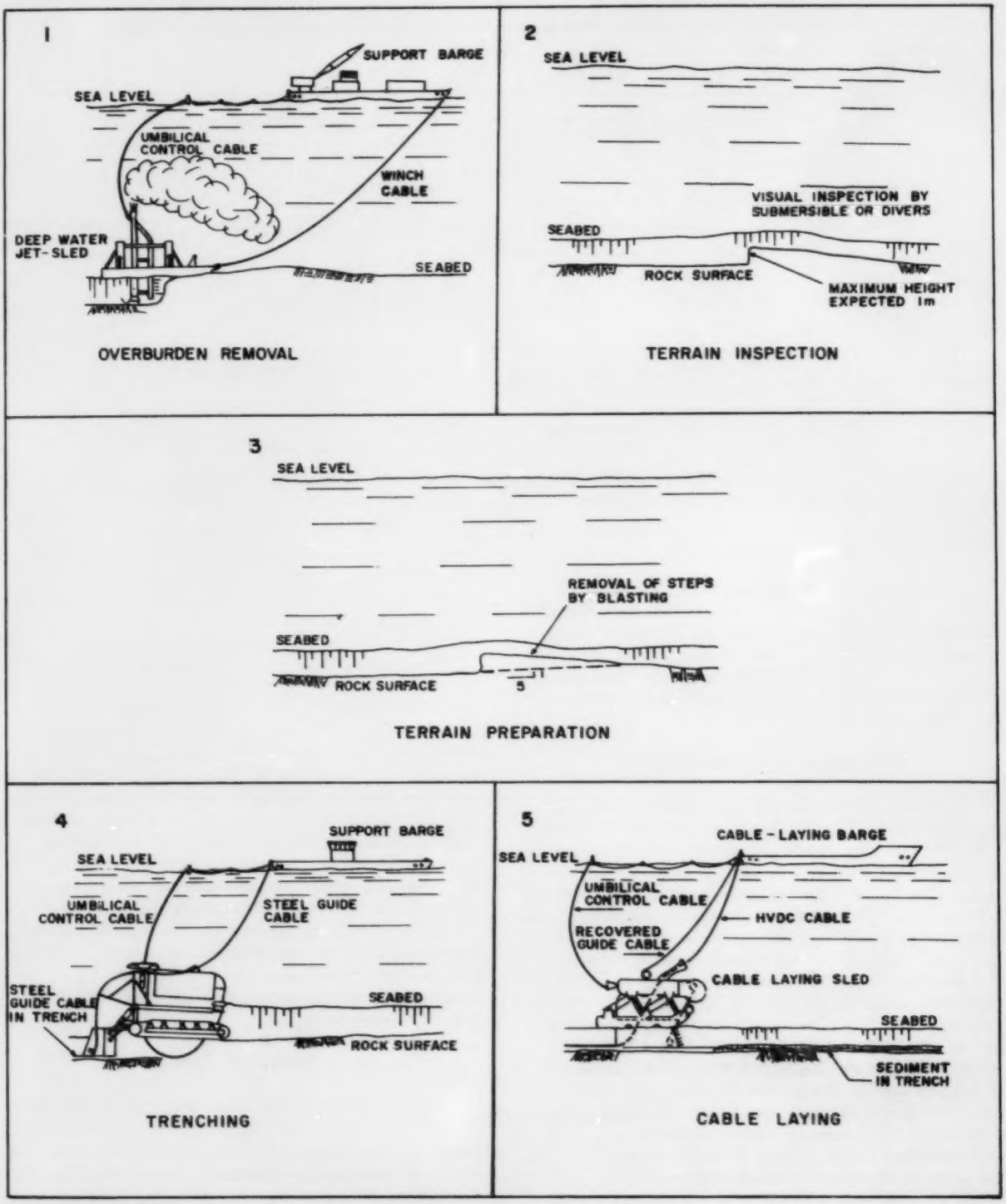

Figure 11. *Proposed sequence of high-voltage, direct-current (HVDC) cable installation in seafloor bedrock trenches (from Lower Churchill Development Corporation, 1980).*

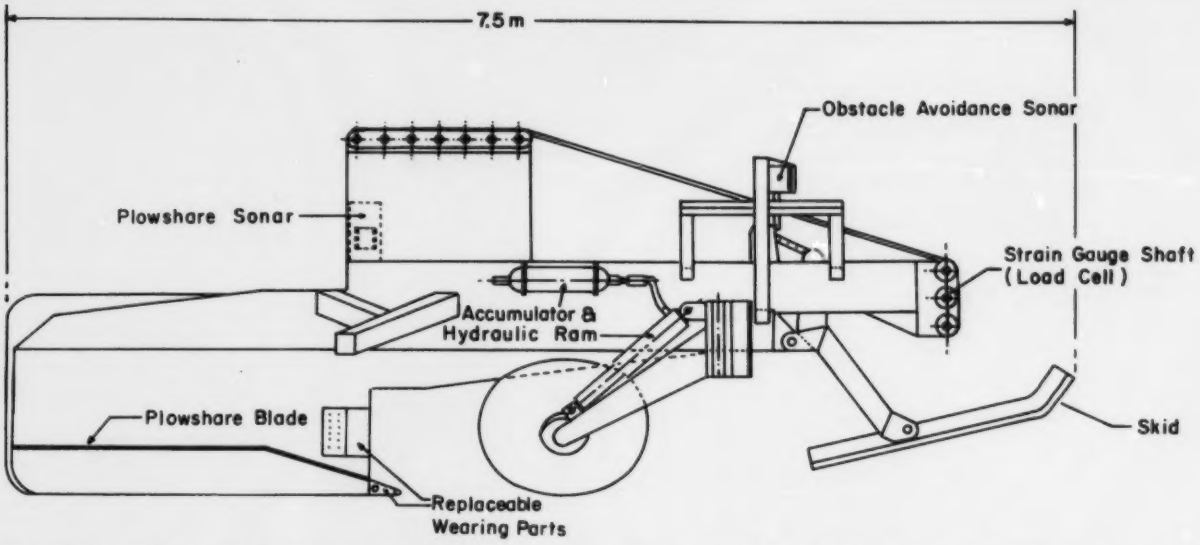

Figure 12. *Side view of the five-tonne prototype cable plough manufactured by ITM Head Wrightson Teesdale Ltd. (from Lower Churchill Development Corporation, 1984b).*

Seismostratigraphy

Glacial drift is stratigraphically the lowermost of the surficial map units, and is recognized on both seismic-reflection profiles and in the boreholes. It has high-intensity surface reflectivity, and internal reflectors are incoherent. The unit is differentiated from the relatively flat-surfaced, acoustically impenetrable bedrock below, and a slightly more transparent overlying unit.

Thickness and Distribution

Drift directly overlies the bedrock across most of the central part of the Strait as a semicontinuous but thin blanket (Map 90-6). In water depths greater than about 80 m, it varies in thickness from a few centimetres to well over 5 m within linear ridge features. The presence of the unit is difficult to confirm on the steep slopes of the Newfoundland and Labrador troughs because much of the acoustic energy is lost by incident reflection off the seabed. However, its presence is inferred above local buried bedding scarps. On Centre Bank North and South, the unit forms a fairly continuous deposit generally about 2 m thick but reaching thicknesses as much as 7 m in isolated pockets (Beaver Dredging Company Ltd., 1981b,d; SNC–Lavalin, 1982b). Between L'Anse-au-Clair (Labrador) and St. Barbe (Newfoundland), the unit is of greater thickness, reaching over 10 m in numerous isolated depressions in the bedrock surface. In this region, drift is less continuous and its subcrop is commonly interrupted by the presence of exposed bedrock ridges.

Offshore from Yankee Point, the drift unit is discontinuous, reaching thicknesses up to 5 m in isolated depressions in the limestone bedrock; it becomes more continuous toward deeper water. At the approaches to Winter Cove, it occurs in isolated pockets filled with more than 5 m of Quaternary deposits, of which the proportion of glacial drift is not known. A narrow 4-km-long east-trending channel originating in Winter Cove is filled with between 5 m and 15 m or more of sediment, possibly of glacial-drift origin.

The distribution of glacial drift near the Labrador coast is also variable. Off Pointe Amour, the surficial deposits consist almost entirely of glacial drift (with the exception of thin deposits of gravel lag). Here it fills depressions in the bedrock surface and thins over bedrock 'highs', resulting in an overall smoother seabed surface. The unit is typically about 5 m thick, reaches over 12 m in depressions, and generally thins to less than 1 m within about 300 m of the shoreline. This contrasts with the thick deposits in Forteau Bay and immediately west of Pointe Amour. However, these deposits are most likely sands (see Sand/Shells later). Near Forteau Point, the deposits are thicker and more continuous than they are farther offshore. In general, they are contained within a broad trough between the shore and Centre Bank, thickening to about 7 m in the Labrador Trough. In this area, the seismic-reflection data do not allow the differentiation of glacial drift within the surficial section.

Linear Ridges

In water depths greater than about 80 m, the upper surface of the glacial-drift unit is characterized by extensive fields of regularly spaced linear ridges. They were first identified from sidescan sonographs (Nova Scotia Research Foundation, 1973) in a small area off Yankee Point, and were interpreted as fault-bounded bedrock ridges. A similar interpretation was made from seismic-reflection data (Kenting Exploration Services Ltd., 1979), which, due to lack of penetration, could not distinguish these ridges from underlying bedrock.

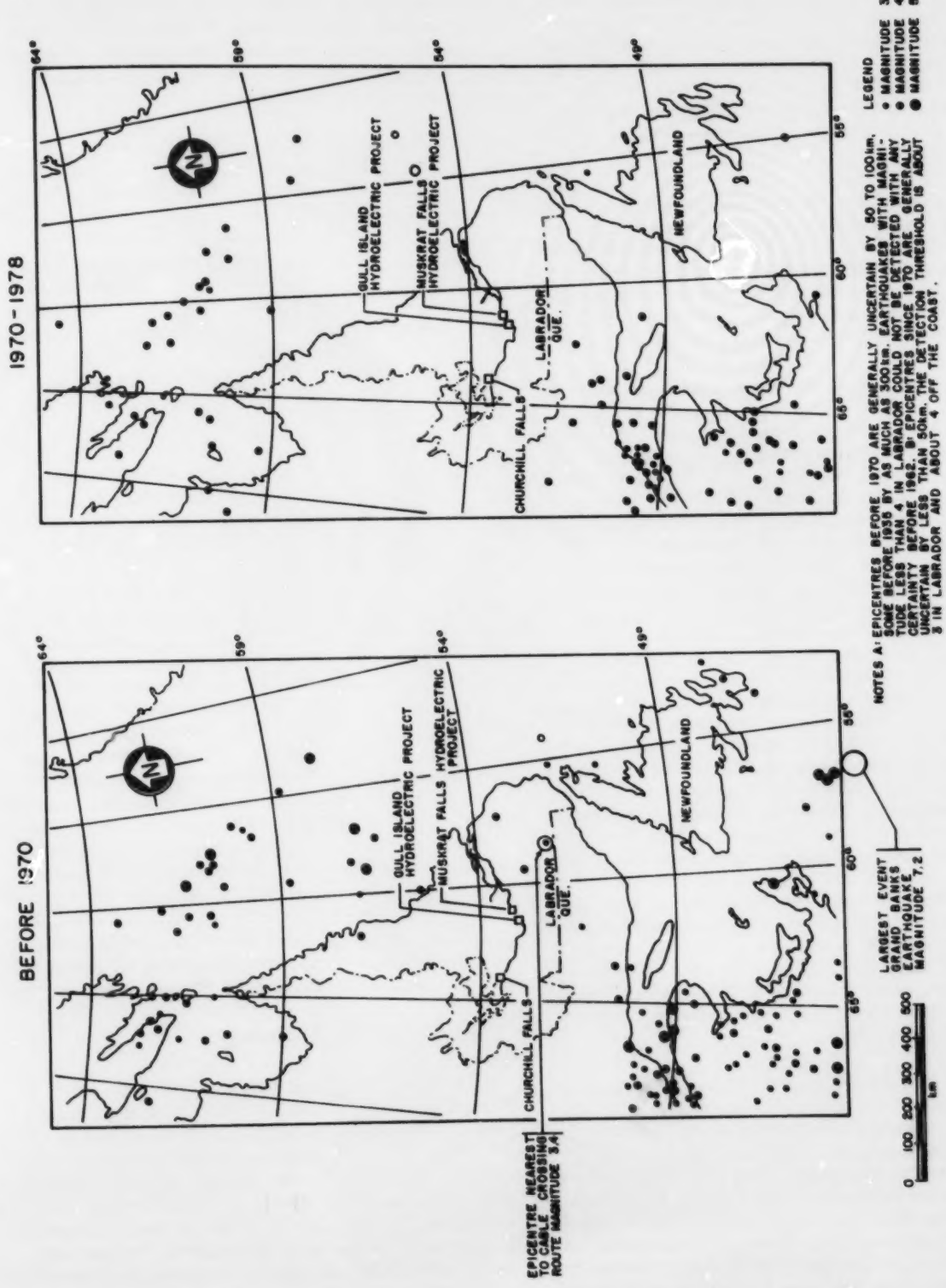
1970-1978
BEFORE 1970
64°
59°
54°
49°
55°
60°
65°
GULL ISLAND HYDROELECTRIC PROJECT
MUSKRAT FALLS HYDROELECTRIC PROJECT
CHURCHILL FALLS
LABRADOR QUE.
NEWFOUNDLAND
EPICENTRE NEAREST TO CABLE CROSSING ROUTE MAGNITUDE 3.4
LARGEST EVENT GRAND BANKS EARTHQUAKE MAGNITUDE 7.2
0 100 200 300 400 500
km
LEGEND
• MAGNITUDE 3-4
• MAGNITUDE 4-5
● MAGNITUDE 5-6
NOTES A: EPICENTRES BEFORE 1970 ARE GENERALLY UNCERTAIN BY 50 TO 100km, SOME BEFORE 1935 BY AS MUCH AS 300km. EARTHQUAKES WITH MAGNITUDE LESS THAN 4 IN LABRADOR COULD NOT BE DETECTED WITH ANY CERTAINTY BEFORE 1962. B: EPICENTRES SINCE 1970 ARE GENERALLY UNCERTAIN BY LESS THAN 50km. THE DETECTION THRESHOLD IS ABOUT 3 IN LABRADOR AND ABOUT 4 OFF THE COAST.

Figure 13. *Earthquake epicentres in eastern Canada recorded between 1900 and 1978 (from SNC–Lavalin, 1980a).*

Guigné and King (*in* Beaver Dredging Company Ltd., 1981b) were the first to interpret them as moraines based on their similarity to extensive fields of 'lift-off moraines' mapped in sub-crop over deep areas of the Scotian Shelf and Grand Banks of Newfoundland (L. King, personal communication, 1981; King and Fader, 1986). In these two regions, King and Fader *(op. cit.)* described ridges from sidescan sonographs in rare occurrences where they outcrop at the seabed.

Ridges in the Strait have been mapped from sidescan sonographs (Figure 14). Information on frequency, height and slope of the ridges was collected by sensors mounted on the seabed plough (Lower Churchill Development Corporation, 1984a, c). In some areas, individual ridges were mapped (Beaver Dredging Company Ltd., 1981b, d) and these are shown on the surficial-geology map (Map 90-6).

Ridge length is not known because sidescan coverage was incomplete. However, Guigné and King (*in* Beaver Dredging Company Ltd., 1981d; Lower Churchill Development Corporation, 1984b) measured partial lengths ranging from about 50 m to over 1 km, with most in the 100- to 200-m range. Spacing of the ridges varies from about 35 m up to 200 m, with most occurring in the range 50 to 100 m. Most of the ridges are linear or sinuous in plan view, and locally may bifurcate; single ridges vary in orientation up to 20°. All measurements of ridge height (Lower Churchill Development Corporation, 1984a; Beaver Dredging Company Ltd., 1981b; Shawmont Newfoundland Ltd., 1984) are given as elevations above the seabed, and as such represent minimum values because they are often partially buried beneath the glaciomarine–marine unit. In the southern part of the map area, Guigné reported that almost 90 percent of the ridges are 1 to 3 m in height and the remainder are in excess of 3 m (Lower Churchill Development Corporation, 1984a). Slopes on the ridge flanks are generally 5 to 10°; one slope was measured at 50°. Across the narrowest portion of the Strait, the ridges are slightly smaller with approximately 10 percent exceeding 2 to 3 m in height. Slopes are similar to those in the south. The ridges are generally uniformly oriented between 040 and 060 (Josenhans, 1981); a small number are between 020 and 100. Onland, ridges interpreted as DeGeer moraines by Grant (1969, *in press*) occur between Hare Bay and the Strait of Belle Isle. The features are parallel bouldery ridges up to 5 m high, 30 to 50 m wide, and spaced about 200 m apart. They occur at elevations between sea level and +90 m (Grant, 1986).

It is uncertain whether any of the offshore boreholes were located on the ridges, so lithological information is lacking. However, the ridges have been observed on photographs, from video and obstacle-avoidance sonar from the test plough and from a submersible. The plough survey showed that cobbles and boulders are the dominant grain size on ridge crests. Using a submersible, Zevenhuizen (1986, p. 13) described 'boulders set in a fine-grained very cohesive clay matrix' on the tops of the ridges. On most of the 62 ridges traversed by the test plough, video data show boulders up to 50 cm in diameter (Lower Churchill Development Corporation, 1984c). Larger boulders from 75 to 100 cm in diameter occur locally, and Zevenhuizen (1986) observed a boulder up to 2.5 m in diameter. Only one ridge revealed a sandy surface containing scattered boulders. The presence of buried boulders in the ridges was inferred from erratic ploughshare penetration and tow-cable tension.

The distribution and spacing of the ridges along a northwest-trending profile between Flowers Cove and Forteau Bay is shown in Figure 15. The ridges occur in two large, isolated areas in the Strait. The most extensive area is in the Newfoundland Trough. The other area is restricted to the Labrador Trough and extends from offshore Pointe Amour to offshore Forteau Point where the Trough narrows considerably (Guigné *in* Lower Churchill Development Corporation, 1984b). The ridges are generally restricted to water depths of greater than 85 m. In general, the upper bathymetric limit of their distribution varies by less than 4 m. The only exceptions to this is where they occur in small, local depressions south of Centre Bank (Figure 16).

Many names have been applied to small, regularly spaced, ice-transverse till ridges. These include washboard, cross-valley, Rogen, cyclic, annual, winter, DeGeer, and ribbed moraines (Flint, 1971; Sugden and John, 1976).

The ridges in the Strait of Belle Isle were originally termed DeGeer moraines by Guigné and King (*in* Beaver Dredging Company Ltd., 1981b; Shawmont Newfoundland Ltd., 1984; Lower Churchill Development Corporation, 1984b). They possess the same characteristics as DeGeer moraines in terms of scale, composition (boulders on top are characteristic), associated glaciomarine (or lacustrine) sediment, and occurrence in broad, open depressions. As originally defined, DeGeer moraines are associated with varved sediments that occur between the ridges, each moraine having a single interfingering varve (DeGeer, 1892). They were originally called annual moraines by DeGeer and were thought to have formed sequentially, on an annual basis, by retreat of an ice sheet from a lacustrine or marine environment. Without better control on the chronology of the features in the Strait, the descriptive term 'ribbed moraine' is preferred in this report. (Interpretation of the genesis of the ribbed moraines follows under 'Discussion'.)

Lithology

The glacial-drift unit occurs almost everywhere in subcrop. It is overlain by one or more of the stratigraphically younger map units and is nearly everywhere covered by the gravel lag unit, which makes sampling of sub-surface units difficult. As a result, the offshore borehole samples (SNC–Lavalin, 1982b; Beaver Dredging Company Ltd., 1981c) are the only ones on which to base lithological descriptions and geotechnical properties of the unit. Additional problems are related to correlating the cores with seismostratigraphy and the offset of borehole localities relative to seismic profiles.

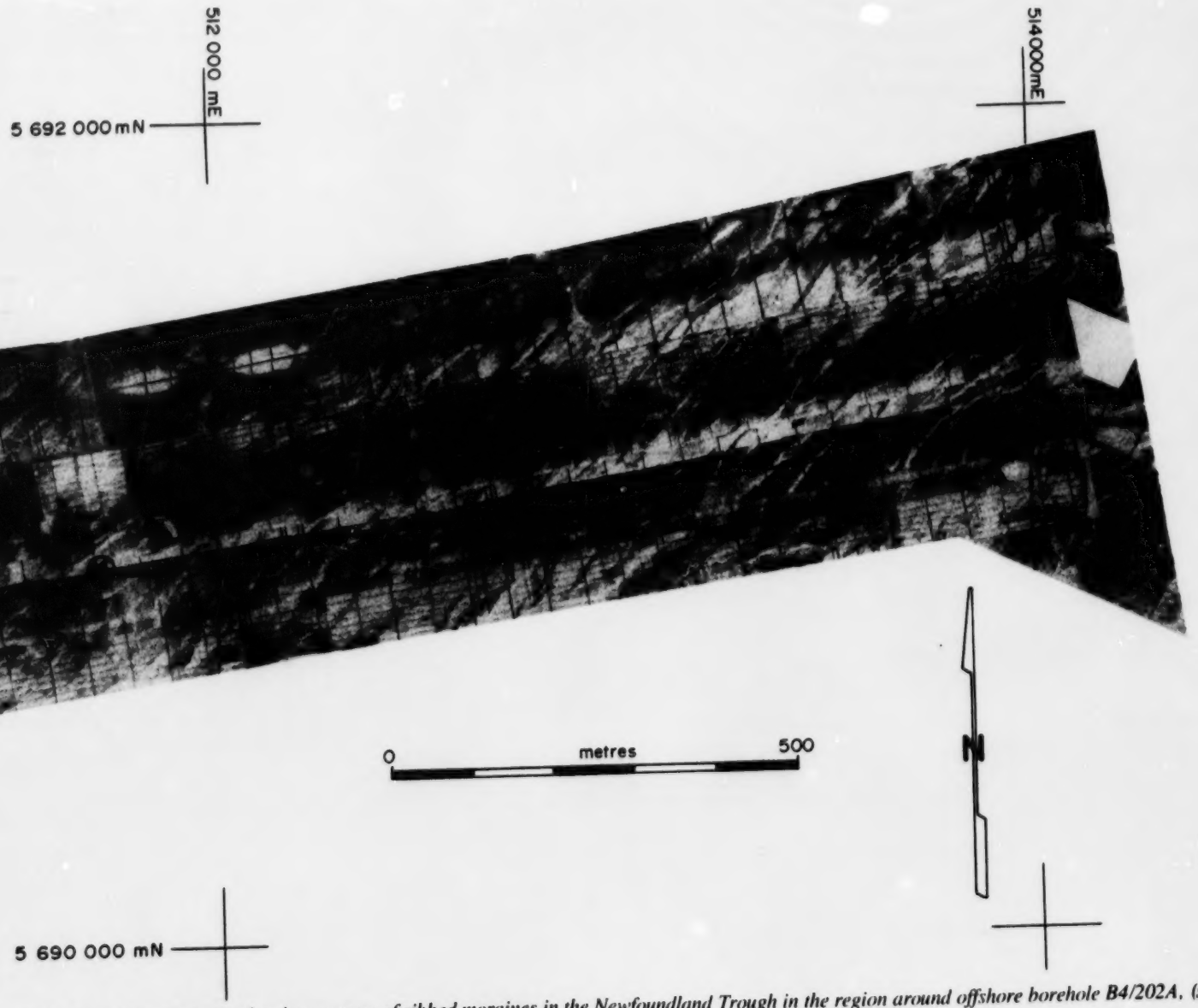

Figure 14. *Part of a sidescan mosaic showing an area of ribbed moraines in the Newfoundland Trough in the region around offshore borehole B4/202A. (survey and mosaic by Geonautics Ltd., reported in Beaver Dredging Company Ltd., 1981d).*

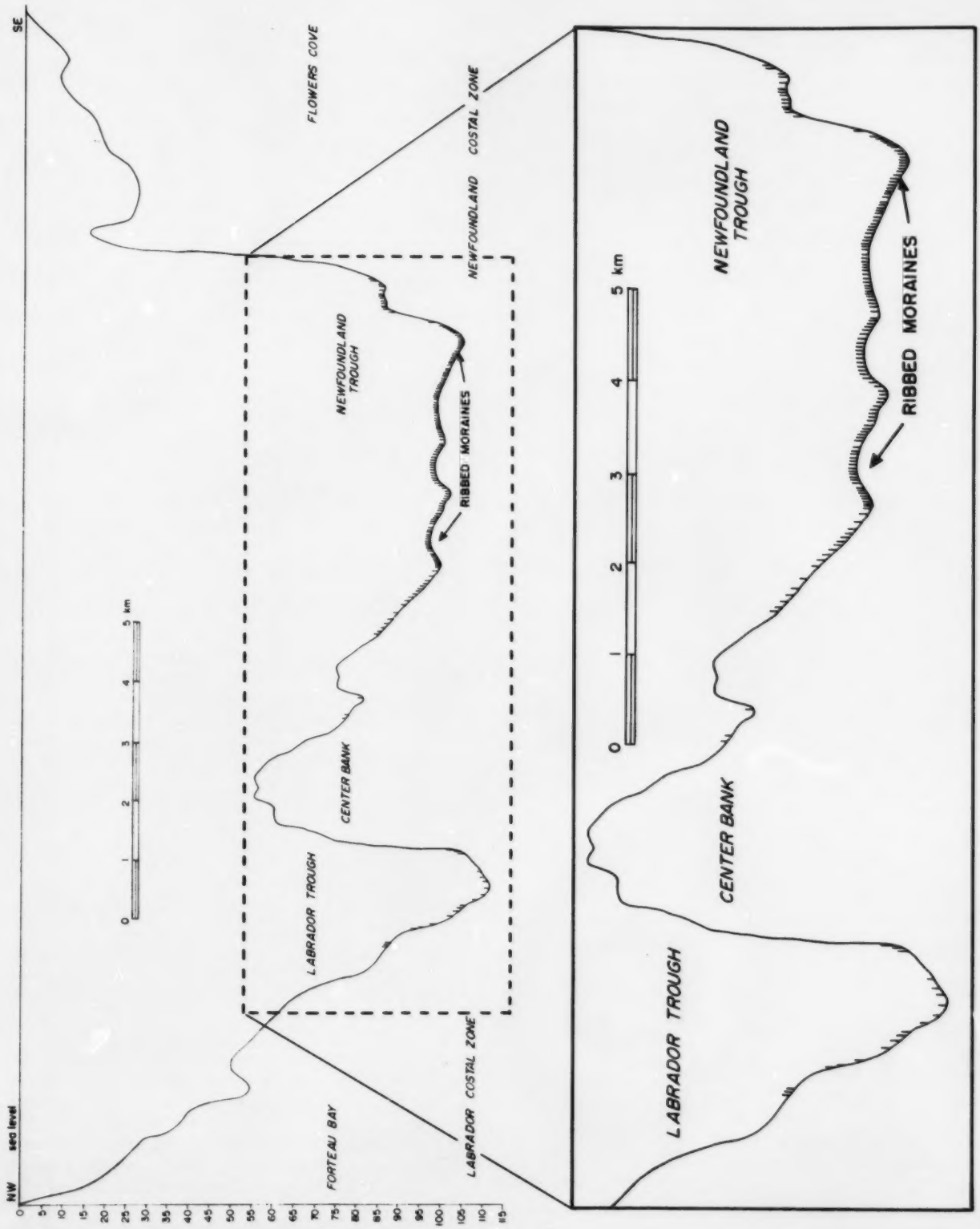

Figure 15. *Bathymetric profile across Strait of Belle Isle from Forteau Bay, Labrador, to Flowers Cove, Newfoundland, showing spacing and depth distribution of ribbed moraines at the seabed. Each short vertical line represents a single moraine ridge.*

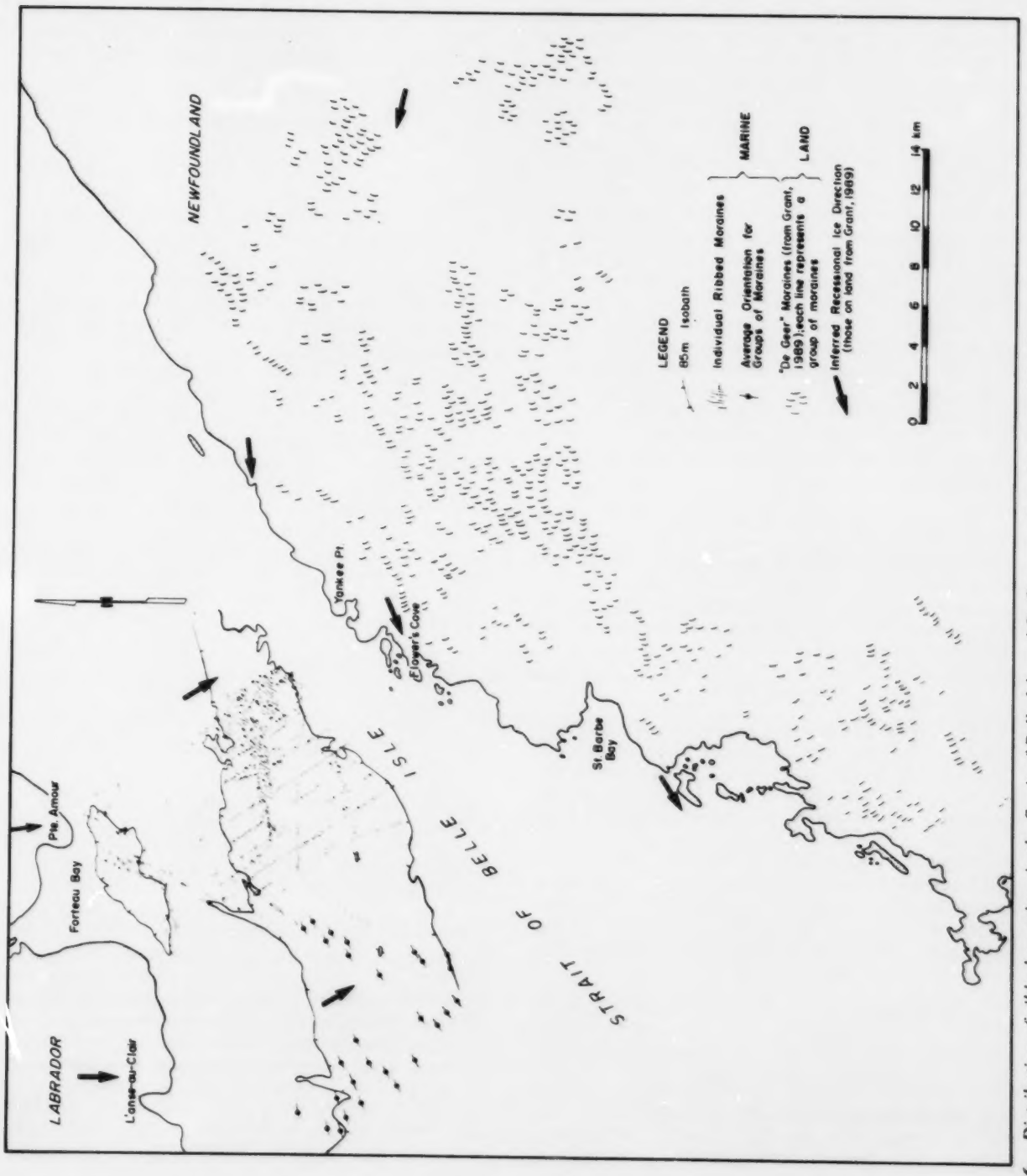

Figure 16. *Distribution of ribbed moraines in the Strait of Belle Isle and DeGeer moraines (as mapped by Grant, in press) onland in Newfoundland. Inferred glacier-flow directions shown by arrows.*

Despite these difficulties, the unit occurs in thirteen boreholes. Three lithologically defined (but unmapped) facies of the unit are identified from the borehole descriptions and interpretations given by SNC–Lavalin (1982b). The first facies is a 'basal till' unit (SNC–Lavalin, 1982b) that rests directly on bedrock and has high-shear-strength values (394 to 1089 kPa; see Table 1). It ranges in thickness from 0.81 m (borehole A4/7C) to 3.78 m (borehole B1/207) and consists of a dense to very dense, poorly to very poorly sorted, massive diamicton (40-percent gravel; 36-percent sand; 13-percent silt; 11-percent clay) containing some cobbles and boulders up to 30 cm in diameter (SNC–Lavalin, 1982b; Beaver Dredging Company Ltd., 1981c). The cobbles and boulders consist of locally derived rock types including sandstone, limestone, and granite. One granite boulder, 48 cm in diameter, was drilled at a locality where the underlying bedrock is Forteau Formation limestone (borehole A4/7). In two boreholes (A5/20 and A11/37), the 'basal till' is overlain by a 'reworked till' (SNC–Lavalin 1982b) of similar grain size and 1 to 1.2 m thickness. Overlying the tills is a diamicton facies described as dense 'sand, gravel, cobbles, and boulders' (SNC–Lavalin, 1982b) whose average grain size ranges from 62-percent gravel, 36-percent sand and 2-percent silt. Table 1 provides results of grain-size and geotechnical analyses of the three facies, and Table 2 shows the correlation of map units with the borehole results.

In seven of the boreholes (boreholes A2/14, A5/20, A8/28, B3/203 [SNC–Lavalin, 1982b], and B1/207, B2/206a, B4/202a [Beaver Dredging Company Ltd. 1981c]), the 'till' is red because it is derived, in part, from the nearby red sandstone of the Bradore Formation (Figure 17). Red 'till' is found mostly in the region between the Labrador coast and the western side of the Newfoundland Trough.

Interpretation

Much of the glacial drift is interpreted as a subglacially deposited till. This interpretation is based on regional distribution of the unit, geometry and thickness, grain-size distribution, the occurrence of ribbed moraines, and the presence of internal erratics. The high-shear strength of the basal part of the unit, indicating overconsolidation, is interpreted to be the result of ice loading. Josenhans (1981) and Zevenhuizen (1986) also interpreted the unit as till based on similarities to tills on the Labrador Shelf. The other subunits of the glacial drift above the basal till are less consolidated and may be ice-margin deposits related to the formation of the ribbed moraines.

A correlation between land and marine units is suggested by SNC–Lavalin (1982b) based on lithological similarity between the borehole till and similar deposits found in four test pits on land near the Newfoundland shore.

GLACIOMARINE–MARINE

Seismostratigraphy

On seismic-reflection profiles, the glaciomarine–marine unit, which overlies the glacial drift, is variable in character and generally occurs in small isolated pockets as a ponded sediment. In areas where it thickens, mainly to the south, the unit consists of continuous coherent reflectors and onlaps against the ribbed moraines and bedrock. In this area, there is good penetration, suggesting the unit is fine grained, containing few sound-scattering pebbles, cobbles and boulders. The upper surface of the unit is usually smooth and parallel to internal stratification. A representative boomer record is shown in Figure 18A.

Thickness and Distribution

The unit occurs mainly in the deeper portions of the Strait, and is usually associated with the ribbed moraines (Map 90-6). Because it lies beneath sand and gravel deposits, the true distribution of the unit is not evident on the surficial map. The unit is thickest near the deepest part of the Newfoundland Trough in water depths between 105 m and 120 m. In this area, acoustically transparent deposits, locally exceeding 10 m in thickness, partially cover the ribbed moraines (Figure 18B).

Lithology

Lithological data for this unit are derived solely from the offshore boreholes, mostly from the Newfoundland Trough, and show it to be lithologically the most variable of all the map units. In most boreholes, poorly sorted sand and pebbles with cobbles and boulders and some silt were encountered (see Tables 1 and 3). Finer grained sediment was recovered in boreholes B3/203 and B4/202A, located in about 100 m of water (SNC–Lavalin, 1982b; Beaver Dredging Company Ltd., 1981c). A 2.1-m-thick section consisting of shell fragments (undated) mixed with silty sand and gravel occurs in B4/202A. In B3/203, a 2.41-m-thick section of very soft to loose silt and clay containing a trace of sand directly overlies bedrock.

Interpretation

The interpretation of these sediments as being of glaciomarine origin is based on a number of factors. It occurs as a ponded deposit between the moraines and rests above the till. This is similar to the association observed by King and Fader (1986), who noted that in the area between 'lift-off moraines' on the Scotian Shelf and the Grand Banks, glaciomarine sediment is everywhere present. Onland, Grant (*in press*) has mapped glaciomarine deposits (stony muds, Unit 4 of Grant, *op. cit.*) containing both deep- and shallow-water marine molluscs, generally at altitudes below +30 m. This unit is described as a massive grey sediment containing roughly equal proportions of sand, silt and clay, and abundant pebble- to boulder-sized ice-rafted clasts. Shell dates place the age of the unit between 11,000 and 7,000 years B.P., and, according to Grant (*in press*), correspond to a fall in sea level from +80 m to +20 m. Grant interpreted the sediment to be derived from 'littoral and fluvial erosion of pre-existing deposits.'

Data from the boreholes indicate the submerged unit is coarser than the onland deposits described by Grant (*in press*).

TABLE 1. Summary of thickness, grain size and geotechnical properties of the surficial map units

MAP UNIT	AREA[1]	MAX. THICK-NESS (m)	GRAIN SIZE (%) GR.	SAND	SILT	CLAY	MAX. GR. SIZE (cm)	STRENGTH	'N' VALUE (BLOWS/ 30 cm)	PRECONSOL-IDATION STRENGTH (kPa)
SAND–SHELLS	Rt. 1	1.34	–	–	–	–		very loose to loose	0-15	–
	Rt. 2	2.21	–	–	–	–		medium dense to dense	12-35	–
GRAVEL LAG	–	–	dom.	com.	–	–	14.0[3]	–	–	–
GLACIO-MARINE–MARINE	Rt. 1	2.4	2	8	43	47[5]	–	very soft to loose	2-4	2.6
	Rt. 2	4.2	3	90	7	–	–	medium to dense	9-44	–
GLACIAL DRIFT[4]	Rt. 1	6.5	62	36	2	–	–	medium dense	9-46	–
	Rt. 2	4.2	–	–	–	–	–	loose to dense	9-44	–
LODGEMENT TILL[2]	Rt. 1	2.4	40	36	13	11	48.05	very dense	29-35	394-1089
	Rt. 2	3.7	18.5	55.5	20.5	5.5	200	very dense	72	470-853

[1] Route (Rt.) 1 is between Pointe Amour (Labrador) and Yankee Point (Nfld.)
Route (Rt.) 2 is between L'Anse-au-Clair (Labrador) and Yankee Point (Nfld.)

[2] Undifferentiated recessional till and glaciomarine sediment; lodgement till is considered a subunit of glacial drift for mapping purposes.

[3] Drapeau (1968)

[4] Pisces IV dive (Josenhans, 1981)

[5] Granite boulder encountered during drilling (SNC–Lavalin, 1982b)

Abbreviations: dom. = dominant; com. = common; gr. = gravel.

It is possible that fine material was not present in the sediment or was winnowed out and deposited nearby in deeper water, under lower energy conditions. Fine sediments are possibly represented by the thicker, more stratified deposits to the west.

GRAVEL LAG

Distribution

Initial studies in the Strait of Belle Isle established the predominance on the seafloor of gravel, with grain size ranging from pebbles to boulders (e.g., Drapeau, 1968). The distribution of gravel (Map 90-6) is interpreted mainly from sidescan-sonar data, with samples provided by other investigations. On sidescan sonographs, gravel appears as a dark tone indicating high acoustic backscatter from a rough surface. Though boulders are known to be present in the gravel areas (Josenhans, 1981; Lower Churchill Development Corporation, 1984a,c), they are not apparent on the sonographs.

The gravel unit occurs in a wide swath along much of the Newfoundland Coastal Zone, often as a discontinuous deposit directly overlying bedrock. In some areas, sand is

TABLE 2. Correlation of surficial map units with the offshore borehole data

SEISMO-LITHOSTRATIGRAPHIC MAP UNITS	SUBUNITS (UNMAPPED)	LITHOLOGICAL UNITS FROM BOREHOLE REPORTS*
SAND–SHELLS		shell deposits
GRAVEL LAG		undifferentiated from 'sand, gravel, cobbles and boulders'
GLACIOMARINE–MARINE	ponded glaciomarine–marine	sand
		silt and clay
	undifferentiated glaciomarine sediment and morainic till	sand, gravel, cobbles and boulders
		reworked till
GLACIAL DRIFT	undifferentiated glaciomarine sediment and morainic till	sand, gravel, cobbles and boulders
		reworked till
	morainic till	
	lodgement till	very dense, silty-sand and gravel basal till containing trace of clay

* SNC–Lavalin (1982b) and Beaver Dredging Company Ltd. (1981c)

a significant component and is thought to overly the gravel or occur directly on the bedrock. In the Newfoundland Trough, gravel occurs as a thin deposit covering the ribbed moraines. Sand containing shells is common between the moraines and may occur as a thin deposit above the gravel. Gravel is common on the gentle southern slope of Centre Bank but numerous sand patches overlie it. On Centre Bank and in the Labrador Trough, gravel lag is dominant with the exception of linear sand ribbons, which occur on the steepest slopes of the bank edge.

Lithology

In the Strait, Drapeau (1968) mapped the presence of 'openwork' gravel, which has no interstitial fines, and a gravel 'mixture', which contains fines. He also noted the presence of coralline algae on exposed clasts, and sand (restricted to Labrador bays). Josenhans (1981) also observed barnacles and a variety of organic growth on exposed boulders, cobbles and pebbles. Drapeau (1968), using maximum grain size, showed that pebbles (<64-mm diameter) occur in 43 percent of samples, and cobbles (65- to 120-mm diameter) occur in 57 percent. Red arkosic sand is a common constituent of the 'mixture', and is derived from the Bradore Formation (Drapeau, 1968). Red sand occurs on the seabed from the Labrador coast to the centre of the Strait, but is never found near the Newfoundland coast. This distribution compares favourably with the extent of red till from the glacial drift, and suggests that the sand fraction is derived from reworking of subjacent till.

Detailed information on the distribution and characteristics of gravel comes from the test-plough video data. These data are presented on maps as narrow strips together with ploughshare-penetration depth, and also as descriptions in table form (Lower Churchill Development Corporation, 1984c). About 40 percent of the seabed along the proposed cable routes between Winter Cove and L'Anse-au-Clair, and Yankee Point and L'Anse-au-Clair, consists of gravel. In contrast, the alternative route from Forteau Point across Centre Bank to an intersection with Route 'B' on the southern side of Centre Bank traverses several small sand patches; gravel occurs along less than 15 percent of the transect. The plough-video description states in all cases that the pebbles, cobbles and boulders rest on top of sand or silty sand.

Interpretation

The gravel is interpreted to be the result of winnowing and removal of finer matrix by currents, resulting in concentration of coarse material in the form of a thin, gravel-lag surface. The lag serves to armour and protect underlying sediments from further erosion. The parent materials from which the surface lag is derived are probably the glacial-drift and glaciomarine–marine units.

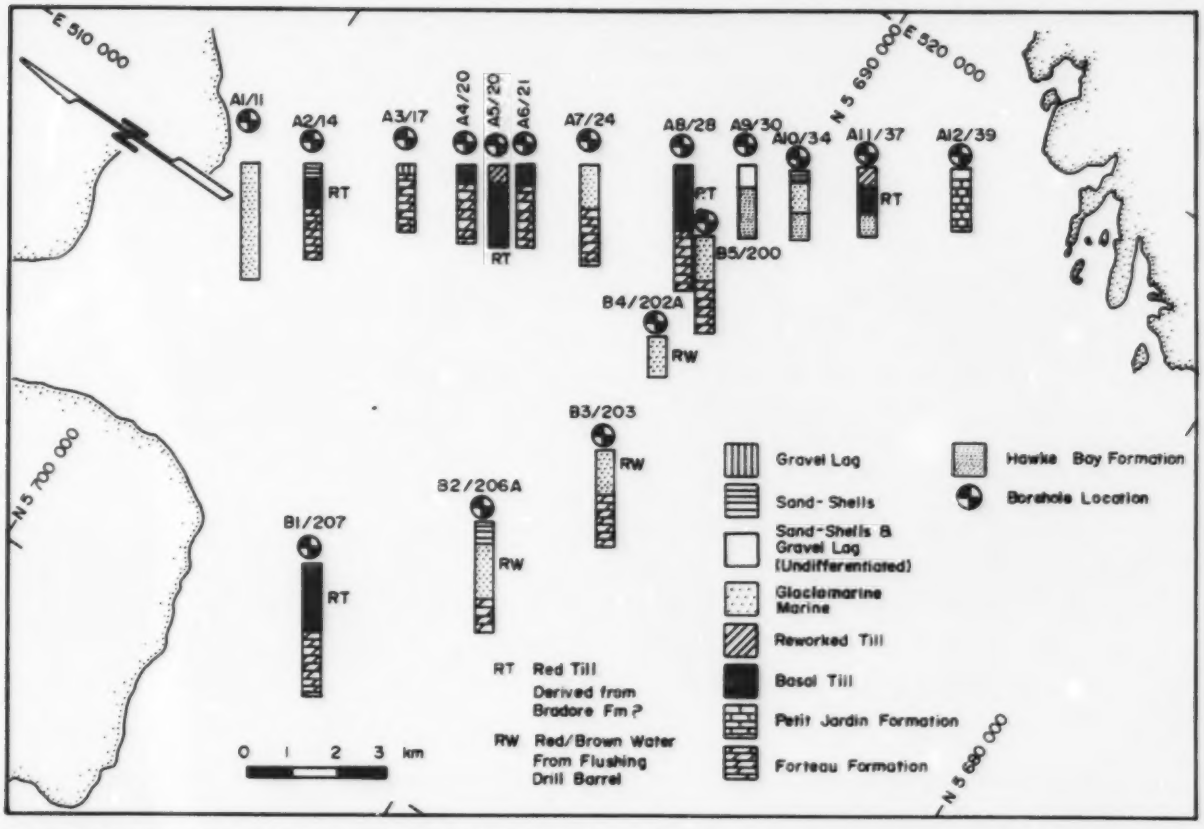

Figure 17. *Map showing bedrock and surficial units in offshore boreholes (adapted from SNC–Lavalin 1982b). Red till is interpreted to have been derived largely from reworking of Bradore Formation red sandstone. Red-brown water from core-barrel flushing may also indicate the presence of Bradore Formation sedimentary rocks in some boreholes.*

Other mechanisms of deposition, including ice rafting, may be important locally, and Josenhans (1981) interpreted perched boulders on the seabed as having been iceberg rafted. Though coralline algae has grown on most, he observed one 'fresh' boulder, indicating recent transport.

Iceberg rafting, although occurring today, was probably more important during ice regression when icebergs were produced locally at calving margins in the Goldthwait and Daly seas. Current winnowing was probably an active process during deposition of the glaciomarine unit, and subsequent winnowing after deglaciation enhanced the development of a lag gravel on the seabed. Current speeds exceed 100 cm/sec (max 1.73 m/s [SNC–Lavalin, 1982b]), well over the critical entrainment velocity for sand and small pebbles (of quartz density) (e.g., Miller *et al.*, 1977).

SAND–SHELLS

Though gravel is the dominant seabed facies in the Strait of Belle Isle, sand and shell 'hash' is locally important. On sidescan sonographs the sand usually appears as a uniform, light tone indicating a smooth surface of low reflectance. In places bedforms occur, the crests and troughs of which are displayed as alternating light and dark tones. Gravel is concentrated in some of the troughs. Where the sand is thick enough to be resolved on high-resolution seismic-reflection profiles, it has a uniform, acoustically transparent character.

The most extensive deposits of sand occur in the bays and inlets of the Labrador coast (e.g., Drapeau, 1968). More recent detailed marine surveys and observations by divers have defined sand thickness and the distribution of bedforms (Kenting Exploration Services Ltd., 1979; Beaver Dredging Company Ltd., 1981b, d; Shawmont Newfoundland Ltd., 1984; Lower Churchill Development Corporation 1984a, b, c).

Forteau Bay contains an extensive sand deposit reaching a maximum thickness of 16 m in bedrock depressions. The presence of bedforms indicates sediment transport in much of Forteau Bay. Megaripples (wave-formed ripples) having wavelengths of less than 5 m generally display an east-trending or southeast-trending crestline in water depths less than 50 m. In water depths between 50 to 75 m, lobate dunes occur averaging 20 to 30 m in width and 1.5 to 2 m in amplitude,

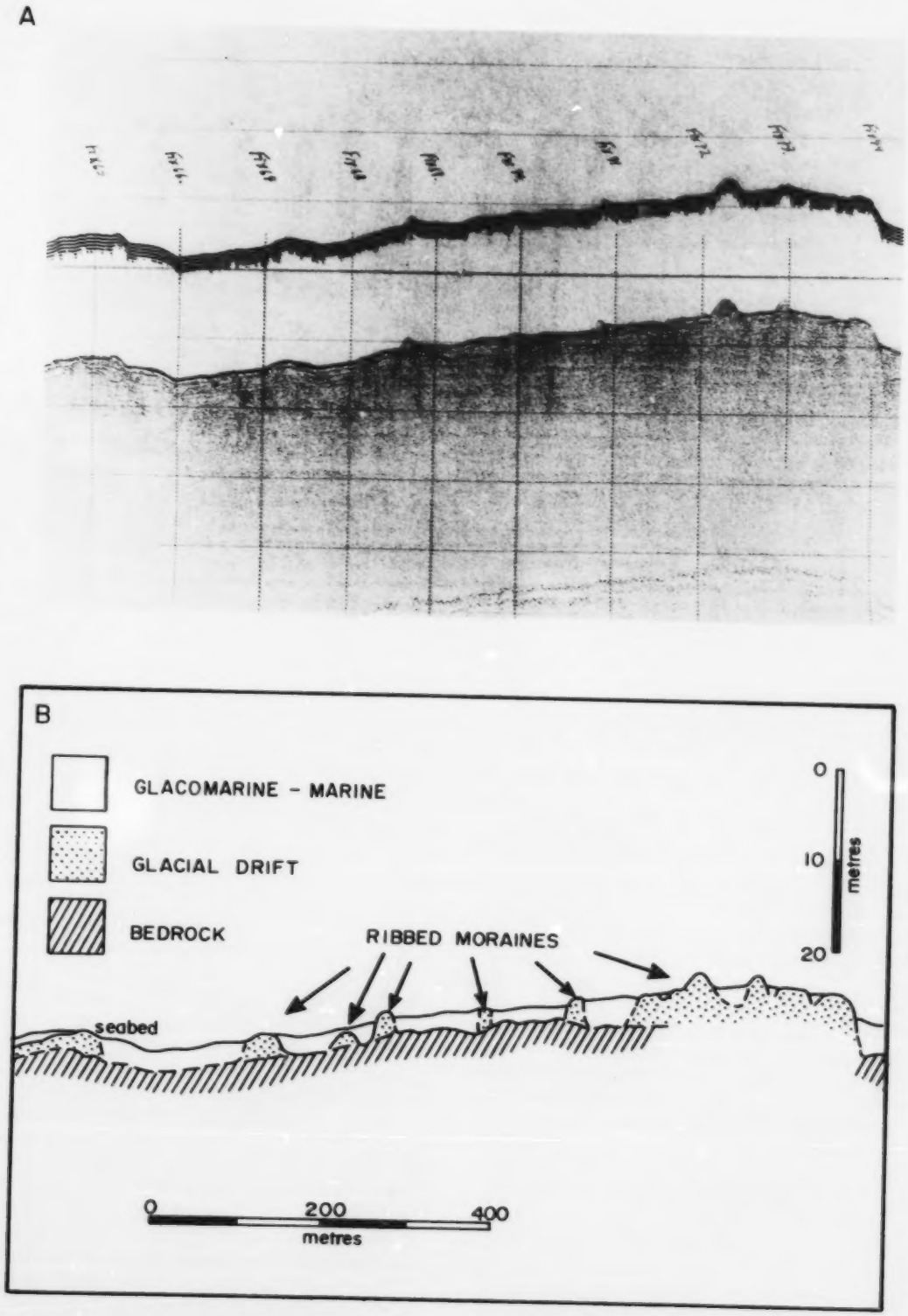

Figure 18. *(A) Representative boomer (Huntec DTS) profile showing strongly reflective deposits of the glaciomarine–marine map unit ponded between ribbed moraines. (B) Line interpretation of above profile outlining the bedrock surface, glacial drift and glaciomarine–marine map units (line Charlie, fixes 65-72; adapted from Lower Churchill Development Corporation, 1984b)*

TABLE 3. Summary of descriptions and interpretations of the surficial map units

MAP UNIT	DESCRIPTION		INTERPRETATION
	LITHOLOGICAL*	ACOUSTIC	
SAND	fine to medium sand and shell 'hash'	light, uniform tone on sidescan; transparent, homogeneous on seismic profiler	sublittoral and current-winnowing products; post-glacial to recent
GRAVEL LAG	gravel, cobbles, and boulders of assorted rock types	uniform, dark tone on sidescan; poorly resolved on profiler	post-depositional current winnowing of underlying glaciomarine and glacial-drift units
GLACIOMARINE–MARINE	locally variable; sand, silt and clay, gravel, cobbles and boulders	poorly stratified on profiler records; transparent to highly reflective	ice-proximal, sub-aqueous outwash
GLACIAL DRIFT; LODGEMENT AND MORAINIC TILL (DIFFERENTIATED)	mainly diamict; locally overconsolidated	strong, discontinuous, incoherent reflections on profiler records	mainly till; ice recessional
BEDROCK OUTCROP			
[A] ISOLATED OUTCROP	Bradore, Forteau, Hawke Bay and March Point formations	distinct areas of irregular, alternating light and dark tones on sidescan; impenetrable on profiler records	
[B] WITH LOCAL SEDIMENT COVER	(as above)	variable, depending on sediment type and distribution	

* see also Table 1

and having wavelengths from 5 to 30 m (Beaver Dredging Company Ltd., 1981b; Kenting Exploration Services Ltd., 1979). Well-developed lee and stoss faces indicate that the dunes are active features. In water depths from 75 to 110 m, megaripples of 5-m wavelength occur. Abrupt changes in crestline orientation suggest a complex hydraulic regime (Kenting Exploration Services Ltd., 1979).

Sand is present in L'Anse-au-Clair extending offshore about 2 km. Maximum thicknesses of 20 m occur in a 500-m-wide bedrock channel extending offshore from the head of the bay. The sand thins to 5 m or less on the channel flanks. Probes pushed into the seabed by divers penetrated up to 5 m of loose sand, suggesting, as in Forteau Bay, that sand constitutes the bulk of the deposit (Lower Churchill Development Corporation, 1984a). The sediment is a fine- to medium-grained sand containing minor shells (95 weight percent <2.0-mm diameter [Lower Churchill Development Corporation, 1984d]). Measurement of seabed elevation at 21 localities in water depths of less than 10 m between two surveys eight months apart showed changes ranging from 3 to 54 cm (Lower Churchill Development Corporation, 1984a), indicating active sediment transport. Calculating total increase and decrease in seabed depth at the localities indicates a net decrease of only 4 mm. This result should not be interpreted as indicating net deposition because the change represents only one set of data points, and small changes could be accounted for by migration of wave-induced bedforms. Offshore from L'Anse-au-Clair, megaripples occur in water depths of 50 to 85 m (Map 90-6).

Probe results and visual observations at Winter Cove on the Newfoundland coast indicate a deposit of loose sand, pebbles, cobbles and boulders containing shells, 1.0 to 2.0 m thick. The sediment is confined to a bedrock channel, which reaches a maximum depth below the seabed of 15 m (Lower Churchill Development Corporation, 1984a) (see Map 90-6). On Centre Bank and on the bank slopes, thin,

irregularly shaped sand patches occur, the shape and distribution of which cannot be determined because of insufficient sidescan-sonar coverage. The surface of the sand patches is generally featureless, and they are too thin to be resolved on high-resolution seismic-reflection profiles. More common are long, narrow sand ribbons and relative paucity of sand, indicative of a flow regime possibly exceeding 100 cm/s (e.g., Kenyon, 1970). Long narrow fields of active megaripples are also present along the bank slopes. Individual ripples commonly exhibit wavy or irregular crestline shapes (termed three-dimensional megaripples), indicative of bottom-current velocities of about 100 cm/s (Dalrymple *et al.*, 1978).

Shell 'Hash'

In the offshore areas, long, linear 'sand streamers', mapped by Guigné (*in* Beaver Dredging Company Ltd., 1981b), are common, occurring most commonly along the northern slope of the Newfoundland Trough (Figure 19 and Map 90-6). The 'streamers' generally occur in the troughs of the ribbed moraines, and are at least 250 m in length (one has been traced for over 600 m). Widths of the 'streamers' vary from several metres to about 30 m. The 'streamers' have been observed from a submersible (Josenhans, 1981; Zevenhuizen, 1986) and are composed of broken shell 'hash' and minor amounts of gravel. The 'hash' consists of loosely packed fragments 1 to 2 cm in diameter; observations of lee and stoss accumulations around boulders on the seabed suggest that the sediment is probably frequently moved by bottom currents. Visual examination from a submersible along one of the test-plough routes (route C) about one year after ploughing showed that in 90-m water depth the trench was filled with shell 'hash' (Zevenhuizen, 1986).

The 'streamers' are similar in morphology to sand ribbons, which are long, regularly spaced, low-amplitude, flow-parallel bedforms formed under a relatively high-flow regime (Kenyon, 1970). Kenyon suggested that sand-ribbon spacing is a function of spacing of the helical spiral currents that are responsible for their formation.

Interpretation

Thin patches of sand may be the product of winnowing of the local till and glaciomarine sediments, and were possibly generated during formation of the gravel lag. The considerable volume of sand in Forteau Bay and L'Anse-au-Clair may be the product of sublittoral erosion of till, outwash, and raised-beach deposits, which are found on the Labrador coast (Grant, 1989). Reworking probably would have been most intense during transgression and regression of the Goldthwait Sea, but recent littoral erosion may play a role.

An active shell fishery in the Strait confirms the presence of living communities, and thus the source of shells that compose the 'streamers' is probably local. Drapeau (1968) noted a local abundance of 'tarnished, bored and eroded shells' on the Labrador side of the Strait, but offered no explanation for this concentration. A summary of descriptions and interpretations of the surficial map units is provided in Table 3.

ICEBERG SCOURS

The presence of iceberg scours in the Strait of Belle Isle has been confirmed from sidescan sonar and high-resolution seismic-reflection profile data. However, there has been difficulty in distinguishing these features from the ribbed moraines because of similar morphological characteristics. In some cases, contradictory interpretations have been made from the same datasets. For example, Josenhans (1981) interpreted the moraine ridges as iceberg-scour berms and described 'boulder rims changing rapidly to consistent-sized pebble clasts at the bottom of the trough with some shell fragments at the base', whereas Guigné (*in* Shawmont Newfoundland Ltd., 1984, p. 20; and *in* Lower Churchill Development Corporation, 1984b, p. 18) interpreted the widespread occurrence of morainic ridges.

Problems have arisen distinguishing between ribbed moraines and iceberg scours because diagnostic morphological criteria and distribution patterns have not been established. The following are used to draw a distinction in this report:

1. Ribbed moraines are restricted in their distribution to the troughs and depressions of the Strait, and do not occur on the banks and upper-flank areas in water depths less than 80 m. Studies of other eastern Canadian continental-shelf regions show that iceberg scours are common throughout a broad range of water depths (e.g., Lewis *et al.*, 1977, 1980; Barrie, 1980; Todd *et al.*, 1988).

2. Bifurcation of ribbed-moraine ridges is commonly observed on sidescan sonograms from the Strait. This is rarely seen in iceberg scours.

3. Uniformly spaced parallel pairs of ridges are characteristic of iceberg scours, and represent seabed material displaced to either side of the scouring keel. Although ribbed-moraine ridges are sub-parallel on a regional scale, they cannot be separated into ridge couples, and commonly, adjacent ridges diverge and converge.

4. Scouring icebergs incise troughs in seabed sediments. High-resolution seismic-reflection profiles from the Strait show that in areas of interpreted ribbed moraines, ridges stand proud of the seabed but there is no evidence of seabed incision between ridges. This is well illustrated in places where isolated ridges lie directly on top of bedrock. It is difficult to envisage how a scouring keel might create a single ridge on a bedrock surface.

From all of the sidescan survey data, only 15 iceberg scours have been identified. Kenting Exploration Services

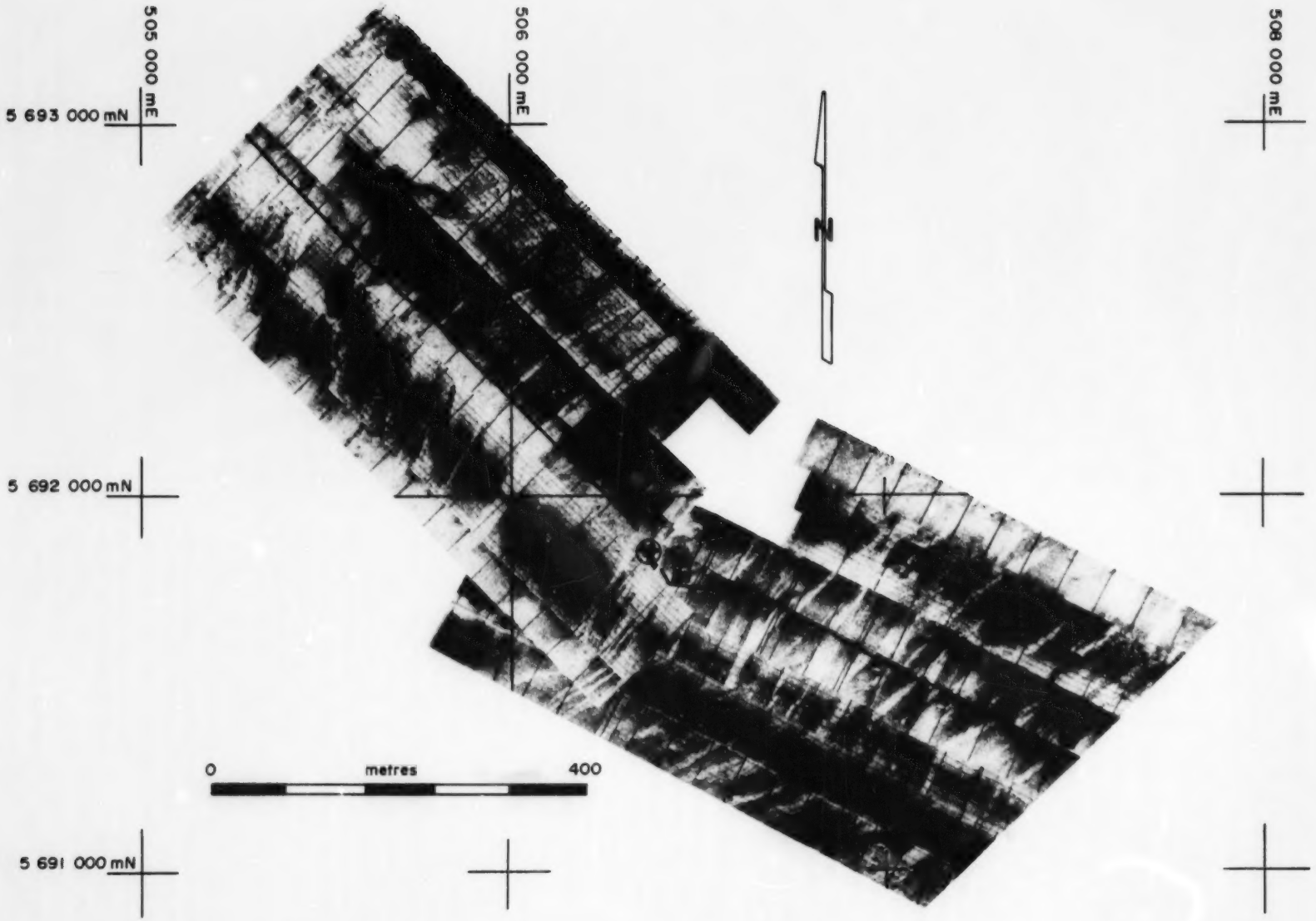

Figure 19. *Part of a sidescan mosaic showing 'sand streamers' in the central region of the Strait. Note the presence of megaripples along the tops of some streamers. Megaripple crests are oriented normal to current flow (survey and mosaic by Geonautics Ltd., reported in Beaver Dredging Company Ltd., 1981d).*

Ltd. (1979) observed eight small scours in water depths between 36 m and 83 m. The largest scour was 10 m wide, 250 m long and 1 m deep. In 1981, seven additional scours were observed in water depths up to 100 m (SNC–Lavalin, 1982b).

DISCUSSION

Pattern of Ice Retreat

A more complete understanding of the retreat of Wisconsinan ice from the Strait of Belle Isle during the Belle Isle and Hare Bay phases may be gained through a comparison of the pattern of the submarine ribbed moraines and the DeGeer moraines mapped onland in Newfoundland by Grant (1969, *in press*). Although both the DeGeer and Ribbed moraines were deposited in the Goldthwait Sea, they occur at different elevations and may have developed in different water depths. The DeGeer moraines are concave and are typically spaced at 200-m intervals, whereas the ribbed moraines are linear and are 50 to 100 m apart (see Figure 14). The ribbed moraines have a dominant northeast-trending orientation, whereas the DeGeer moraines swing in orientation from approximately northwest along the Newfoundland coast at a locality well south of the map area, to a north-trending orientation east of the map area, near the head of Hare Bay (Grant, 1986) (see Figure 16). The offshore and onshore moraines probably represent the most recent deposits directly associated with glacial ice in both areas, and may have formed when the Laurentide and Long Range–Hare Bay ice sheets separated in the final stages of retreat from the Strait of Belle Isle. Grant (*in press*) associated the DeGeer moraines with ice retreat toward Newfoundland, with the moraine ridge-crest orientations showing a progressive swing toward the Hare Bay residual ice cap.

Grant (*in press*) suggested the presence of a zone of contact between Newfoundland and Labrador ice. The position of this junction can now be more accurately placed. The northwesternmost DeGeer moraines on land are located near the coast and are part of the main moraine field that continues farther inland. The nearest ribbed moraines, in the offshore region, are all north of the steep escarpment of the Newfoundland Trough about 3 km from the shoreline (see Figures 15 and 16). The escarpment thus may mark the northern limit of a zone of confluence, acting as a barrier to the flow of Laurentide ice. Resistance to flow would also have been compounded by the effect of northward-moving Newfoundland ice.

A schematic representation of the hypothesized progressive decline and retreat of the two ice sheets is shown in Figure 20. Position 1 shows the surface of the Laurentide ice sheet when its terminus lay near the Grey Islands in White Bay (the White Hills phase of Grant's [*in press*] Long Range Glaciation), and is based on a simple theoretical ice profile equation given by Nye (1959):

$$h^2 = \frac{2A}{pg}(L-x)$$

where h is the thickness of the ice sheet, A is a constant determined by roughness of the bed, L is the distance from the ice centre along a horizontal line, x, p is ice density and g is gravity.

The second stage of retreat (Belle Isle phase of Grant, *in press*) shows the increasing relative influence of Newfoundland ice and the development of a zone of confluence. The third stage shows thin, nearly buoyant ice, developing at the zone of confluence, which migrated to the southern edge of the Newfoundland Trough. In response to calving at the head of Esquiman Channel, as suggested by Grant (*in press*), the ice may have become thin, developing a concave surface profile. In the fourth stage, ice is thinnest at the zone of confluence and becomes buoyant, facilitating the separation of Labrador and Newfoundland ice.

During ice retreat across the Strait, sea level is assumed to have been at the marine limit (approximately 150 m) as defined by Grant (*in press*). This is a reasonable approximation of former water depths because: a) a near-buoyant condition of the two thin ice sheets would trigger rapid breakup and retreat, and b) the Bradore Moraine, which is developed at nearly the same elevation as the marine limit, may represent the subsequent stabilization (stillstand?) margin of Laurentide ice. The coincidence of sea-level and ice-margin positions suggests that the marine limit may have provided this stable position after rapid retreat from the Strait (e.g., Grant, *in press*). Further, the distribution of ribbed moraines is strongly water-depth dependant suggesting their formation was controlled by sea level (see Genesis of Ribbed Moraines, this report). If they were formed at the rapidly retreating ice margins, and if there is a genetic connection between the marine limit and the Bradore Moraine, then the ribbed moraines probably formed just prior to development of the marine limit and the Bradore Moraine. Grant (*in press*) assigned an age of 12,600 years B.P. for the Bradore Moraine based on correlations with the Piedmont Moraines on the west side of the Northern Peninsula, from which the dated shell material came.

The above hypothesis imposes constraints on the relative timing of formation of the marine- and land-moraine fields. Presumably the retreat of the western margin of Newfoundland-based ice began at the head of the Esquiman Channel as suggested by Grant (*in press*). Ice-margin retreat to the north across the Strait of Belle Isle could not have begun in the narrow part of the Strait until the Laurentide and Newfoundland ice sheets became independent, by which time some of the land-based moraines would have formed. Grant (1969) dates the DeGeer moraines as older than 10,900 years B.P. from marine shells incorporated in till of the Ten Mile Lake Moraine, which truncates them. Grant (*in press*) suggests that if the DeGeer moraines are related to annual-retreat phases, then they were formed during a 400-year period.

Genesis of Ribbed Moraines

The literature is rich in controversy over the mode of formation of small ice-transverse moraines. Sugden and John (1976) provided a concise overview of the different forms and

proposed depositional models. Discussion generally centres around the environment of formation in relation to position of the ice terminus, why they occur in fields, and mechanisms controlling their morphology and spacing. Some features can clearly be assigned a proglacial origin owing to the presence of stratified ice-contact deposits mixed with till. Others, such as Rogen Moraines, are apparently subglacial in origin and are commonly formed in association with flutes and drumlins. They may form at the intersection of ice compressional or tensional thrust planes with the glacier bed (e.g., Prest, 1968; Lundqvist, 1969). Others may form from till that has been squeezed into basal crevasses in the ice (e.g., Hoppe, 1952; Gravenor and Kupsch, 1959; Stalker, 1960; Zilliacus 1987, 1989). The mechanism of upward-squeezing of saturated till into basal crevasses is discounted as a mechanism for generating the ribbed moraines in the Strait of Belle Isle because they commonly lie directly on bedrock where there is little or no till available. Recent studies in the nearshore region of the Scotian Shelf have identified similar moraines resting on bedrock (G. Fader, personal communication, Atlantic Geoscience Centre, 1989). However, some aspects of Zilliacus' (1987) model, such as the water-depth control on distribution and formation near a buoyant margin, have similarities with the model proposed here.

Most theories on the formation of Rogen moraines suggest a subglacial origin associated with flow-transverse, patterned, failure planes at the base of active ice. Changes in basal stresses immediately proximal and distal to ice fractures lead to particle migration, pressure melting and lodgment of sediment at the base of the fracture planes to form ridges. This process may be associated with compressional shearing along thrust planes. Compressional shear normal to flow direction occurs in topographic depressions, or could also arise due to longitudinal thermal variations in the ice. Some authors favour moraine formation in tensional cracks (e.g., Lundqvist, 1969), at the base of which till is deposited from debris-rich ice. If this occurs when the ice is actively flowing, the moraines may be modified, leading to the development of commonly observed longitudinal flow-fluted or cross-ribbed surfaces. Fluting related to longitudinal flow is not seen on the surfaces of the ribbed moraines in the Strait.

King and Fader (1986) proposed a model for submarine flow-transverse moraines on the Scotian Shelf and Grand Banks of Newfoundland, and more recently King *et al.* (1987) described similar features on the mid-Norwegian Shelf. These authors suggest the name 'lift-off' moraine for these features. They stress the ice-recessional nature of the moraines as well as structural control by basal-ice fractures, which govern their distribution pattern. However, there is some uncertainty as to whether the moraines are simultaneously developed in fields or as sequential features near a retreating buoyancy line (L.H. King, personal communication, 1989).

Holdsworth (1973a, b) proposed a model for the formation of cross-valley moraines, thought to be presently forming in a proglacial lake at the margin of the Barnes Ice Cap in central Baffin Island. They occur as debris accumulations 50 to 100 m long and 50 to 80 m thick, in the wedge-shaped space immediately in front of the buoyancy line beneath an ice ramp (a semi-floating, tapered, terminal ice lobe). Forward-squeezing of the debris by basal sliding, and backward rotation of the calving margin help to shape the moraines. Holdsworth (1973a, b) suggested that the size of the moraines will be a function of debris-supply rate, stability of the ramp configuration, rate of calving and amount of post-depositional ice pushing. Moraine spacing would therefore be a function of mass balance, which affects the position of the ice margin and calving frequency, which is, in turn, a function of water level and ice thickness. Holdsworth (1973a, b) and Loewe (1969) used the descriptive term 'sublacustrine moraines', but this is inapplicable to moraines found in the Strait of Belle Isle. However, the concept of a buoyant, calving margin is applicable.

Solheim and Pfirman (1985) described a rhombohedral pattern of linear ridges having relief of about 5 m and spacing from 20 to 50 m on the seafloor in front of Brasvellbreen glacier (Svalbard) in water depths from 30 to 100 m. The pattern is interpreted to be the imprint of relief on the glacier sole during stagnation after a surge between 1936 and 1938. The ridges are interpreted to have formed by squeeze-up of seafloor material into basal fractures. Retreat of the glacier after stagnation took place through calving. Discontinuous arcuate ridges, adjacent and subparallel to the modern ice front, are about 25 m wide and 2 to 5 m high, spaced about 17 to 21 m apart (Solheim, 1988), and are interpreted as being caused by minor annual oscillations of the present grounding line. The rhombohedral pattern is dissimilar to the ribbed moraines in the Strait of Belle Isle, and the size of the Brasvellbreen features is considerably smaller.

The existence of compressional shear thrusts at the base of a thin ice sheet, and buoyancy considerations imparted by rising sea level may be used to explain the formation of the ribbed moraines in the Strait of Belle Isle. As noted earlier, the moraines are prolific in both the Newfoundland and Labrador troughs up to a water depth of 80 to 85 m, above which they do not occur. Rare exceptions are a few moraines that occur on Centre Bank between 75- to 80-m water depth. This cut-off elevation strongly implies control of ribbed-moraine formation by sea level. The most likely place where sea level would be expected to influence an ice sheet is at, or close to, the terminus of a buoyant or near-buoyant ice sheet.

Prior to the northward retreat of Laurentide ice across the Strait, it may have experienced compression due both to confluence with northward-flowing Newfoundland ice (Grant, *in press*) and abutment against the southern escarpment of the Newfoundland Trough. This may have generated a pattern of compressive shear thrusts oriented normal to the direction of ice flow, roughly parallel to the grain of the topography. Assuming a relatively even upper surface for the ice sheet as shown in Figure 20, then thickness of the Laurentide ice sheet would have gradually increased northward across the Strait. Some variation in thickness would have resulted from local changes in bedrock topography. As Laurentide ice began

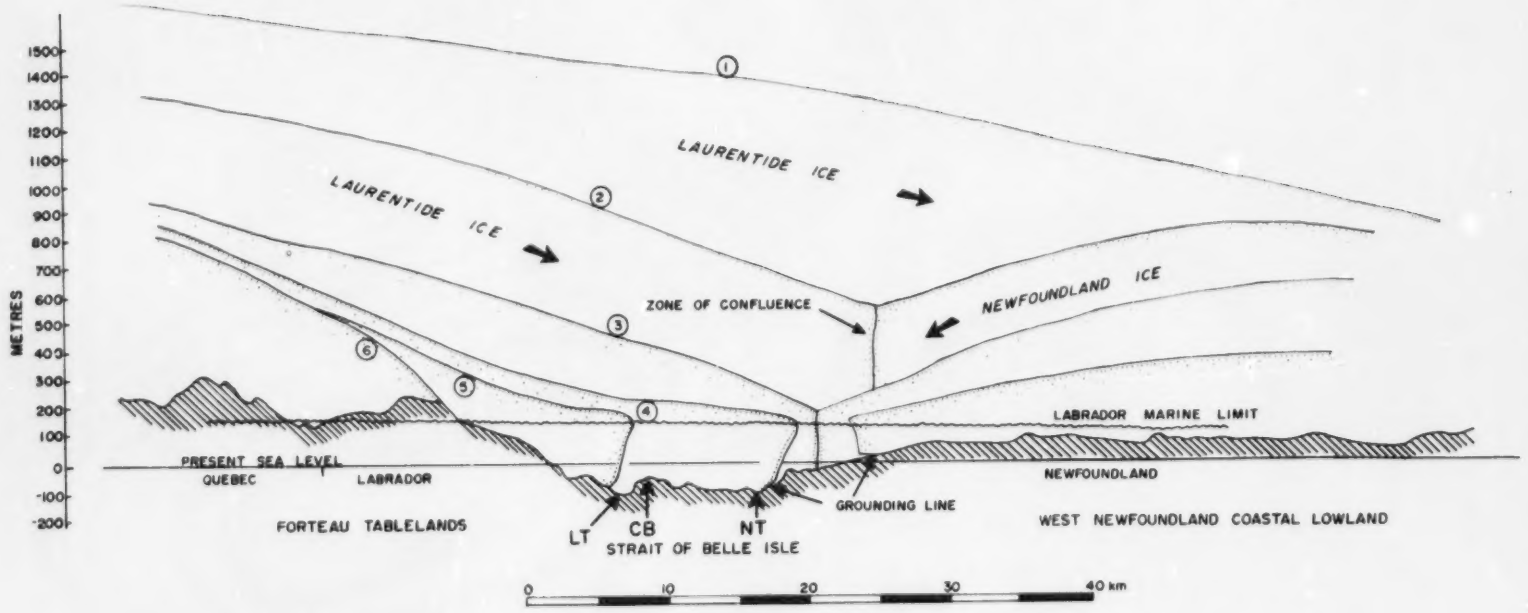

Figure 20. *Schematic cross-section showing inferred sequential (1-6) retreat of Laurentide and Newfoundland ice throughout glacial recession along a NW-SE profile from the coastal lowlands of Newfoundland, across the Strait of Belle Isle, to the tablelands of Labrador.*

The Wisconsin ice maximum surface (position 1) is a theoretical calculation (Nye, 1959; equation # 10 where the basal shear stress is set at 95 KPa) assuming the ice margin extended as far south and east as the Grey Islands (according to Grant, in press*). The position corresponds to the White Hills Phase of the Long Range Glaciation (Grant,* in press*). The position of the marine limit and degree of crustal tilt is also from Grant (*in press*).*

Position 2 is an intermediate stage (corresponding to the Belle Isle Phase of the Long Range Glaciation; Grant, in press*) during which marine drawdown and probable calving into the Gulf of St. Lawrence have become effective. In the zone of confluence between the two ice sheets, flow is toward the reader.*

Position 3 represents the time at which near-buoyant ice has retreated north to the Strait of Belle Isle region.

Position 4 represents initial lift-off on the southern side of the Strait and separation of the two ice masses.

Position 5 is the time of ribbed-moraine development in the Strait (corresponding to the Hare Bay Phase of the Long Range Glaciation; Grant, in press*) before retreat and stabilization at the Bradore Moraine in Labrador (position 6) at approximately 12,600 years B.P. (Grant,* in press*). LT = Labrador Trough, CB = Centre Bank, NT = Newfoundland Trough.*

retreating from the vicinity of the Newfoundland side of the Strait, ice in the Newfoundland Trough would have become buoyant as the margin ablated. Water depth would have determined the critical minimum ice thickness for lift-off near the terminus (sea level was about 80 m higher than present). Increasing ice thickness to the north would have prevented all the Laurentide ice in the Strait from becoming buoyant simultaneously. Instead, the buoyancy line would have retreated progressively (partially through calving?) up-ice from the terminus.

As ice decoupled from the seabed at the grounding line, it would have been unconstrained by bottom effects and may have experienced extension resulting in the generation of basal tension cracks (e.g., Zilliacus, 1987, 1989;) These cracks may have developed along weaknesses in the ice inherited from the compressional phase. Deposition could have occurred at the grounding line where ribbed moraines may have formed sequentially, or in crevasses immediately up-ice of the grounding line where the moraines may have formed in synchronous groups (e.g., Zilliacus, 1989). If they formed as synchronous groups, then complete decoupling of ice from the seabed in the vicinity of the terminus is implied, otherwise flow-parallel fluting of the ribbed-moraine crests by the moving ice would be expected to have developed. Intersecting fracture planes could give rise to observed bifurcation of the moraines.

Deposition is envisaged to be a subglacial aquatic process. Proximal to the ice margin, a high-energy glaciomarine environment is postulated (see Glaciomarine–Marine) based on the coarse nature of the debris. A strong subglacial efflux combined with strong bottom currents may have helped to concentrate and winnow these coarse deposits. The absence of ribbed moraines in the shallower waters of Centre Bank can be explained by buoyancy loss as the margin of the Laurentide ice retreated across this area. Assuming that the former water depth and ice-surface profile remained fairly constant, then the ratio of ice thickness to water depth on the Bank would have increased, causing loss of buoyancy. As ice retreated into the Labrador Trough, a buoyant condition would have been restored and deposition of the moraines again reactivated. From this region to the Bradore Moraine, ice would once more have been grounded, precluding further ribbed-moraine formation.

There was probably no significant relative sea-level change during the time of formation of the ribbed moraines because the critical buoyancy depth (approximately 80 m present depth) was nearly the same on both sides of the Strait. Therefore, this period of time was probably relatively short.

It is possible to estimate the minimum thickness of Laurentide ice at the grounding line by following the concept that ice retreat across the Strait probably occurred at the same time as maximum sea level was reached (marine limit). The sum of the depth of relative sea level at the time of the marine limit (about 150 m above present sea level) and the upper limit of the occurrence of ribbed moraines (the 'buoyancy depth', about 80 m below present sea level), gives a minimum former water depth for the grounding line of about 230 m. Thus, minimum ice thickness (assuming 90 percent of a floating ice mass is below sea level) would have been about 255 m. Newfoundland ice at the grounding line associated with the DeGeer moraine field exposed above sea level (Grant, *in press*) would have been considerably thinner.

ICEBERG SCOURING

GENERAL STATEMENT

Icebergs are acknowledged as posing the greatest risk to submarine transmission cables (Preece, Cardew and Rider, 1964). Most icebergs entering the Strait of Belle Isle in the Labrador Current originate at the calving margins of west Greenland outlet glaciers and drift south along the Labrador Shelf toward the Strait. On average, between 60 to 90 icebergs of the over 600 that reach that latitude each year drift into the Strait (Preece, Cardew and Rider, 1964), the greatest number being seen in May and June (Dawson, 1868). Dawson (1868) was the first to report on the anticlockwise circulation of icebergs in the Strait, most of which enter on the Labrador side and exit on the Newfoundland side. This drift pattern correlates with the observed inward flow of Arctic water on the northern side, and the dominant outward flow of Gulf water on the south side (Huntsman *et al.*, 1954). Of those that enter the Strait, only 6 to 12 small icebergs per year (drafts less than 55 m) pass completely through into the Gulf of St. Lawrence (Briggs, 1969). The remainder drift back and forth with the strong alternating tidal flows, which can reach velocities of 4.6 km/h (Snow, 1968; Briggs, 1969), before passing out of the Strait to the northeast. Some icebergs run aground in depths as great as 110 m and may remain grounded throughout the summer (Snow, 1968). The greatest number of icebergs observed in the Strait at one time was 496, recorded by the Belle Isle lighthouse keeper on May 30, 1858 (Dawson, 1868). Some of these were as long as 800 m and 60 m high.

ICEBERG GROUNDINGS

Monitoring of icebergs using land-based radar stations was conducted between 1979 (Roche, 1980) and 1981 (SNC–Lavalin, 1982c), and in 1986 and 1987 (H. Young, personal communication, Newfoundland and Labrador Hydro, 1988). From these data, positions of grounded icebergs were determined (Figure 21). In an independent survey in 1982, icebergs were also monitored in the Strait by the Canadian Coast Guard (Shea, 1983). The purpose of monitoring was to assess the drift patterns and grounding positions of icebergs with respect to potential submarine cable routes. Between June and November 1981, 66 icebergs were monitored in the Strait. Eight grounded in water depths between 15 to 75 m with grounding periods from 6 hours to

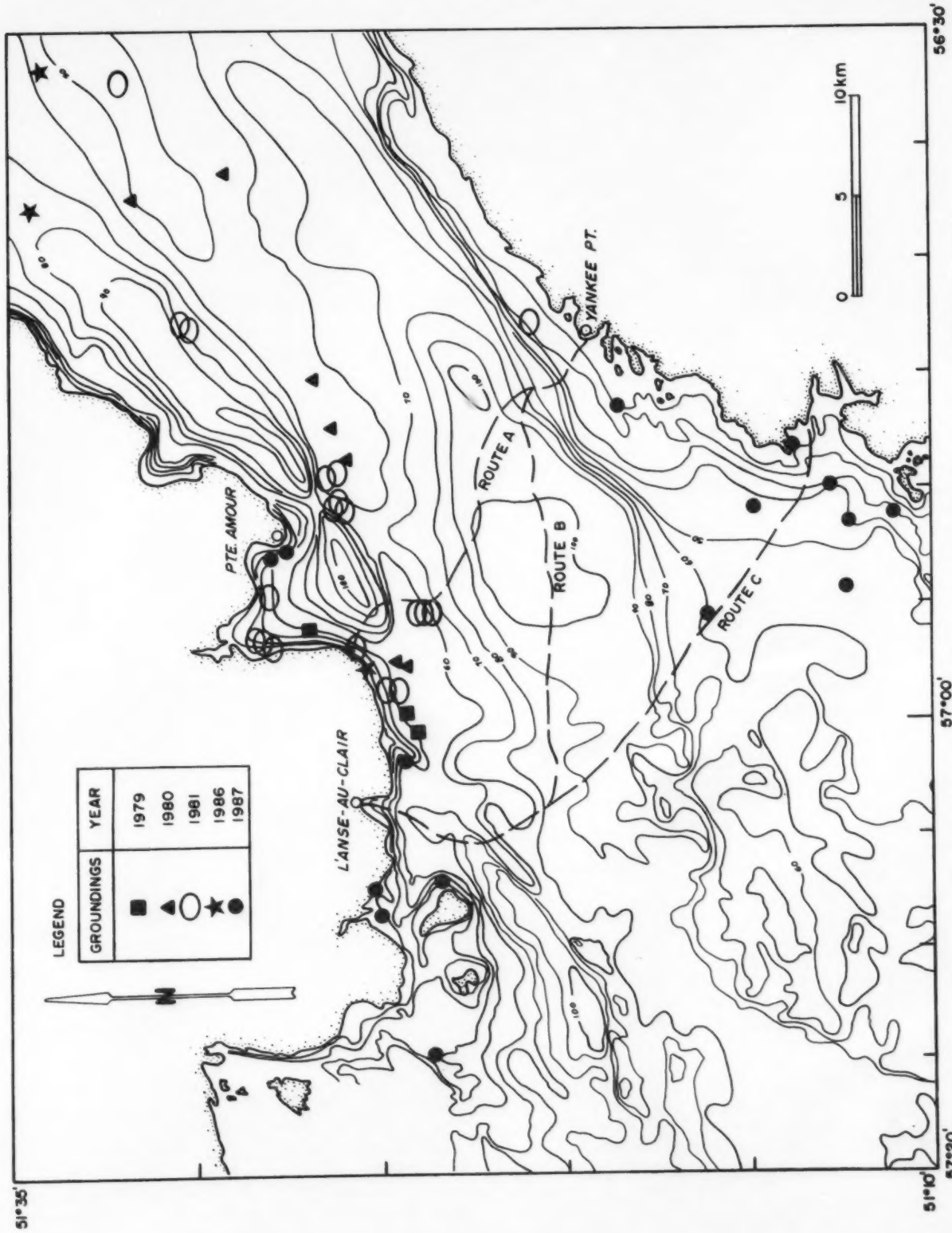

Figure 21. *Distribution of iceberg groundings in the Strait of Belle Isle between 1979 and 1987.*

4.27 days (SNC–Lavalin, 1981). Some of these icebergs grounded more than once, and in total 16 grounding events were recorded. During the observation periods from 1979 to 1981, and in 1986 and 1987, a total of 32 positive groundings was identified (H. Young, personal communication, Newfoundland and Labrador Hydro), the deepest grounding being located on the 60-m isobath. The number of groundings bears no relation to the number of iceberg scours reported on the seabed from sidescan-sonar surveys. As stated earlier, only 15 scours have been identified (Kenting Exploration Services Ltd. [1979] who reported 8 scours; SNC–Lavalin, [1982b] who reported an additional 7 scours), and dimensional information was only reported for one. As a result, a scour database for the Strait of Belle Isle does not exist.

The dearth of reported scours is possibly a result of lack of sidescan coverage, and probably, more importantly, a result of sediment transport, which, in the relatively shallow waters of the Strait, may rapidly erode and fill in scours (cf. obliteration of the test-plough trench by shell 'hash' in 90-m water depth along route C). The phenomenon of removal of scours from a population by sediment transport has been documented for parts of the Grand Banks (Lewis and Barrie, 1981).

Briggs (1969) calculated the horizontal force of a grounding iceberg weighing 260,000 tons with a 55 m draft, moving at 4.6 km/h, to be 51,484 kg if it uniformly decelerates to zero velocity in 10 minutes. If the same iceberg decelerates to zero velocity in 30 seconds, the horizontal force would be 1,029,672 kg.

The presence of a 70-m-deep shoal area between Watts Point and Carroll Point was thought to act as an iceberg filter, preventing those with drafts in excess of 70 m from entering and scouring the seabed in the Strait. However, the presence of iceberg scours and the observation of groundings (Snow, 1968) in water depths as great as 110 m (SNC–Lavalin, 1980a; Nova Scotia Research Foundation, 1974b) inside the Strait forced a re-appraisal of the concept of bathymetric sheltering. Kollmeyer (1979) suggested that wedge- or pyramid-shaped free-floating icebergs that drift over the shoal have the potential to rotate and increase their drafts sufficiently to touch down and scour on any part of the seabed within the Strait. The potential for draft increase has been modelled by Lewis and Bennett (1984), who suggested that draft increases are almost as likely as decreases, whereas Bass and Peters (1984) indicated that icebergs may increase draft by as much as 50 percent, with an average of 25 percent. If this is true, then some free-floating icebergs that drift across the 70-m shoal may be capable of increasing their drafts to 105 m, making all but the deepest areas of the Strait (120 m) potentially accessible to grounding and scouring, agreeing with the interpretation of Kollmeyer (1979).

Kollmeyer *(op. cit.)* estimated a maximum probability of iceberg scouring occurring along an optimized (deep) cable route to be 0.3 events in every 100 icebergs. In a separate study, Miller (1981), using Monte Carlo analytical techniques, estimated scour probabilities of 0.5 events in every 100 icebergs in water depths greater than 75 m, and 0.1 events in every 100 icebergs in water depths below 85 m. Belkin *et al.* (1982) suggested the maximum probability of scouring at some point along the entire length of cable route A of an unburied cable is as great as 11.5 impact events for every 100 icebergs that cross the cable. If the cable along route A is buried (and thus assumed to be completely protected from scouring) from shore to the 70-m isobath, and left exposed in water depths greater than 70 m, then the maximum probability decreases to 2.3 scouring events for every 100 icebergs. Lamberg Consultants (Canada) Inc. (1982) considered the greatest mean probability of scouring across potential cable routes to be 1.3 events per 100 icebergs.

UPSLOPE AND DOWNSLOPE SCOURING

The results presented on scouring frequency are based on assumptions that the 70-m-deep Watts Point–Carroll Point shoal prevents icebergs of deeper drafts from entering the Strait, and those that do enter may only increase their drafts and scour on the other side of the shoal as a result of rotation. Although Belkin *et al.* (1982) noted that tilting of scouring icebergs is possible as they move into shallower water, the concept of upslope and downslope scouring was not developed. Studies of the behaviour of scouring icebergs and of iceberg scours clearly shows that scouring keels may maintain bottom contact as they move upslope and downslope (Barrie, 1980; Woodworth-Lynas *et al.*, 1985; Ruffman, 1985).

Analysis of sidescan sonographs from the Labrador Sea shows that iceberg scours may traverse large (at least 15 m) ranges in bathymetry (Woodworth-Lynas *et al.*, 1986). Analysis of iceberg trajectories from radar sightings suggests that scouring icebergs may traverse across bathymetric ranges as great as 45 m (Woodworth-Lynas *et al.*, 1985). These observations, when applied to the Strait of Belle Isle, suggest that icebergs having drafts exceeding 70 m can enter the Strait and continuously scour. A problem with the analysis of iceberg trajectories from radar sightings is that although grounded (stationary) icebergs can be readily identified, continuously moving, scouring icebergs cannot be detected. Woodworth-Lynas *et al.* (1985) were able to interpret possible scour tracks by using the criterion that if an iceberg identified as grounded began moving into water that was shallower than the grounding depth, and assuming no decrease in draft, then the iceberg was likely scouring the seabed. This method of identifying scouring icebergs probably underestimates the actual number because it cannot distinguish continuously scouring icebergs that have not stopped (grounded) at some point in their recorded trajectories.

Although all of the recorded groundings in the vicinity of the proposed cable routes within the Strait occur in water depths of less than 60 m (see Figure 21), the possibility that scouring can occur in depths greater than this does exist. The observation of iceberg scours as well as of actual groundings in water depths of 100 m and 110 m respectively in the Strait supports such a conclusion. Unfortunately there are no data

either on scour depth or depth of sub-scour disturbance from scours identified in the Strait. This makes decisions difficult concerning what, if any, burial depth is safe for the protection of power cables from iceberg scouring. Analysis of sediments from beneath ancient scours formed in clays of glacial Lake Agassiz, southern Manitoba, indicates that the depth of disturbance can extend to at least 3 m below the scour trough (Woodworth-Lynas and Guigné, 1990). Results of experimental scour modelling in a saturated silt bed suggest that the depth of disturbance can extend to at least five times the scour-incision depth (Poorooshasb *et al.*, 1989).

SUMMARY AND CONCLUSIONS

BEDROCK AND ENGINEERING GEOLOGY

Information on subsurface bedrock geology has been derived almost entirely from borehole information. A re-appraisal of deep seismic-reflection data collected in 1973, 1974 and 1975 indicates that they are of poor quality, and reliable stratigraphic and structural interpretations cannot be made. Bedrock data come form two boreholes at Pointe Amour (73-B-D2 drilled to 150 m, and 74-B-D2 drilled to 305 m), one borehole at Yankee Point (74-B-D1, drilled to 549 m), two shot holes near Yankee Point (Site 'A', 8 km south of Yankee Point, and Site 'B', 8 km northeast of Yankee Point, both drilled to 99 m), and from 16 offshore boreholes (average drilled depth of bedrock is 2.5 m). The nomenclature of bedrock units has been clarified by recognition of the Middle to Upper Cambrian March Point and Petit Jardin formations in the Yankee Point borehole (74-B-D1) and in two nearby shot holes (A and B), units that were previously ascribed to the Hawke Bay Formation. As a result, the March Point and Petit Jardin formations can be extrapolated to occur up to 3 km offshore from Yankee Point.

The initial design concept for transmission cables was to install them in an 18.28-km-long bedrock tunnel 580 m below sea level. The tunnel, accessed by two shafts whose construction was begun at Yankee Point and Pointe Amour in 1975, was to have been 4.25 m wide and 5 m high. An alternative scheme was to lay the cables on the seafloor between two bedrock tunnels extending from shore to the 85-m isobath. A final option was to install the cables in either seafloor bedrock trenches or in overburden trenches using conventional ploughing methods. The latter, cheaper method makes use of deep natural troughs along the route to minimize the risk of damage from grounding and scouring icebergs and from fishing activity.

A total of 488 eathquakes has been detected between 1900 and 1978 in eastern Canada, of which 27 may have been felt in the Strait of Belle Isle. The recommended design maximum acceleration for bedrock-founded structures in the region is 10 cm/s^2.

SURFICIAL GEOLOGY

Four acoustically defined surficial units have been recognized. The stratigraphically lowest unit, glacial drift, lies directly on bedrock as a discontinuous thin deposit (generally from 2 to 7 m thick with local pockets more than 10 m thick) in the central part of the Strait. Ribbed moraines, found in areas generally below the 80-m isobath, are composed of this unit, which reaches thicknesses greater than 5 m at the ridge crests. A glaciomarine–marine unit, locally exceeding 10 m in thickness, overlies the glacial drift and commonly occurs in areas between individual ribbed moraines. Gravel lag occurs as a thin discontinuous surface deposit reworked by strong currents from the underlying glacial drift and glaciomarine–marine units. Sand and shell 'hash' occurs as a thin surface deposit. Sand is found on the floors of bays and inlets on the Labrador coast, reaching thicknesses up to 20 m. Shell 'hash' generally occurs as flow-parallel streamers between the crests of the ribbed moraines.

ICE RETREAT

The confluence between south-flowing Laurentide and northwest-flowing Long Range–Hare Bay ice is interpreted to have been in the vicinity of the southern escarpment of the Newfoundland Trough. The restricted distribution of ribbed moraines generally below the 80-m isobath is interpreted to be related to buoyancy and decoupling of the Laurentide ice sheet. The moraines may have been deposited as synchronous groups along subglacial fractures beneath the floating ice margin. Decoupling of the ice sheet may have occurred in water depths of about 230 m, which is the altitude of the marine limit (150 m above present sea level) plus the depth of the upper limit of the ribbed moraines (about 80 m below present sea level). Thickness of the floating ice was about 255 m. The interpretation of contemporary sea level being at the marine limit at the time of ribbed-moraine formation is reasonable because the moraine cut-off depth implies rapid ice retreat, the retreat halting briefly at the Bradore Moraine in Labrador, on which the marine limit is incised. These events took place before 10,900 years B.P. (minimum age of the DeGeer moraines on land) and possibly before 12,600 years B.P., a date inferred by Grant (*in press*) for the formation of the marine limit on the Bradore Moraine. As Laurentide ice retreated, the Long Range–Hare Bay ice also retreated, probably rapidly, across the Newfoundland Coastal Zone, depositing a suite of 400 annual(?) DeGeer moraines as reported by Grant (*in press*).

ICEBERG SCOURS AND SCOURING

A total of 32 icebergs was observed to have grounded in the Strait in water depths up to 60 m for two periods between 1979 and 1987. However, sightings by local residents indicate that some icebergs may ground in depths as great as 110 m. Scouring icebergs, those in seafloor contact and

having continuous forward movement, could not be identified from the data. This information deficiency is important because it is possible for free-floating or scouring icebergs to pass over the 70-m-deep shoal area between Watts Point and Carol Point and increase their drafts so that they may touch and scour the seabed in water depths up to 105 m. Such deeply scouring icebergs could not be interpreted and would be omitted from the dataset. Icebergs may also scour upslope and downslope, which means that bathymetric sheltering may not prevent scouring icebergs from reaching potential cable routes.

Only 15 scours have been positively identified from sidescan sonograms. This number seems anomalously low considering both 1) the number of grounding events recorded during 5 years of observations and the potential for unrecognized scouring events in the radar dataset, and 2) the potential for a cumulative record of postglacial grounding and scouring events in unconsolidated sediments. Some icebergs probably ground and scour on exposed bedrock surfaces and leave no trace, whereas others affect surficial sediments. Scours may be subsequently affected by strong tidal bottom currents, which winnow and erode them soon after their formation. It appears that the scour record may be incomplete and the effect of iceberg scouring thus underrepresented.

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APPENDICES

APPENDIX A. Summary of rock tests on core samples from *Yankee Point* borehole (74-B-D1), *Pointe Amour* borehole (74-B-D2) and from the 1981 *offshore* boreholes (adapted from SNC–Lavalin, 1982b and Golder Associates, 1982. Test procedures are given by Golder Associates, *op. cit.*)

SAMPLE NO.	ROCK FORMATION	SEISMIC VELOCITY (m/s)	DEPTH (m)	ROCK TYPE	PETROLOGICAL ANALYSIS	SPECIFIC WEIGHT		HARDNESS (g/cm³)	
YANKEE POINT						DRY	WET	SHORE	SCHMIDT
N1	MARCH POINT FORMATION LIMESTONE & SHALE	6100	45.8-46	CRYSTALLINE LIMESTONE	DONE				
N2			74.2-74.4	CALCAREOUS SANDSTONE	DONE	2.71			
N3	HAWKE BAY FORMATION SANDSTONE & SHALE	4575	123-123.2	LITHOGRAPHIC LIMESTONE	DONE	2.66	2.50		
			135.1-135.6	GLAUCONITIC SANDSTONE	DONE	2.49	2.66	72.3	59.7
N4			177.5-177.7	ORTHOQUARTZITIC SANDSTONE	DONE	2.71	2.55		63.6
N5									
N6	FORTEAU FORMATION LIMESTONE	6100	262.7-262.9	CRYSTALLINE LIMESTONE	DONE			52.55	58.4
N7			303.7-303.9	LIMESTONE (CALCARENITE)	DONE	2.88	2.80		
N8			307.5-307.7	CALCAREOUS SANDSTONE	DONE				
N9			356.8-357	ARKOSIC SANDSTONE	DONE				
N10	BRADORE FORMATION ARKOSIC SANDSTONE & ORTHOQUARTZITE	4575	370.1-370.4	ORTHOQUARTZITIC SANDSTONE	DONE			68.65	59.3
N11			401.8-402	SANDSTONE	DONE	2.77	2.60		
N12			467.1-467.3	ARKOSE	DONE				
N13	PRECAMBRIAN GRANITE & GRANITE GNEISS	6037	534.9-535.1	GRANITE	DONE	2.78	2.51	66.5	61.7
POINTE AMOUR									
L1	FORTEAU FORMATION LIMESTONE & SHALE	6100	204-20.6	CALCAREOUS SANDSTONE	DONE				
L2			40.7-40.9	SANDSTONE	DONE				
L3			47.7-48	ARKOSIC SANDSTONE	DONE				
L4	BRADORE FORMATION ARKOSIC	4575	83.7-83.9	ARKOSIC SANDSTONE	DONE				
L5	SANDSTONE & ORTHOQUARTZITE		97.3-97.5	ARKOSIC SANDSTONE	DONE				
L6			113.8-114	ARKOSIC SANDSTONE	DONE	2.61	2.56		
L7			118.9-119.2	ARKOSE	DONE				
L8			132.1-132.3	GRANITIC ARKOSE	DONE				
L9	PRECAMBRIAN GRANITE & GRANITE GNEISS	6037	220-220.3	METAMORPHOSED QUARTZ SYENITE	DONE	2.89	2.59	81.6	56.6
L10			262-262.2	ARKOSE	DONE				

APPENDIX A. (Continued)

	STATIC ELASTIC PROPERTY				POINT LOAD INDEX		SLAKE DURABILITY
	UNIAXIAL COMP. STRENGTH		YOUNG'S MODULUS	POISSON'S RATIO			Id^2 (%)
TOTAL $H_T=H_R/H\alpha$	DRY (MPa)	WET (MPa)	(M/Pa)	(r)	AXIAL (P/d^2) Is50(MPa)	DIAMETRAL Is50(MPa)	
	216.6	248.9	32380	0.22	7.1	9.7	
	25.1	21.3		0.08	4.9	6.0	99.0
	49.3	18.5		0.20	4.7	2.6	98.9
26.7-133.5	114.4	51.0		0.18	3.9	5.3	99.2
142.2-238.0	186.4	170.1		0.13	3.1	5.6	
92.3-109.2	82.3	100.9		0.26	5.3	5.6	98.6
	49.6	105.5		0.36	6.2	5.0	
	243.2	252.3		0.24		9.3	
	127.9	141.6		0.15	6.9	4.3	
132.6-221.9	100.8	117.7		0.21	6.8	5.8	98.4
	68.1	73.5		0.12	7.6	6.2	
	57.1	70.9		0.28	6.2	4.3	
106.9-204.6	126.2	113.0		0.13	7.2	5.9	98.0
	42.6	88.7		0.28	4.6	5.3	
	46.8	62.8		0.12	6.3	3.8	
	95.0	64.4		0.12	4.6	3.5	
	62.9	50.5		0.11	3.6	3.6	96.6
	55.3	66.1		0.11	5.9	1.3	
	28.6	16.7		0.14	2.2	1.5	
	49.7	20.3		0.14	3.4	2.3	
	63.8	72.5		0.24	4.6	2.0	
98.0-187.7	94.8	144.9		0.18	9.7	7.5	
	39.8	41.2		0.25	1.7	2.2	97.8

APPENDIX A. (Continued)

BOREHOLE	DEPTH (m)	ROCK TYPE	PETROGRAPHIC ANALYSIS	BULK S.G. (g/cm³)	SILICA CONTENT BY WEIGHT %	SCHMIDT HARDNESS	UNIAXIAL COMPRESSIVE STRENGTH MPa (PSI)	YOUNGS MODULUS (10 x 6 PSI)	POISSONS RATIO
OFFSHORE									
A2/14	2.12-2.15	FORTEAU FORMATION LIMESTONE		2.69					
A3/17	1.42-1.6	FORTEAU FORMATION LIMESTONE FELDSPAR <1%	CALCITE 85% QUARTZ 15%		53		130 (18850)	7.9	0.24
A4/7C	1.94-2.0	FORTEAU FORMATION LIMESTONE		2.684					
A6/21	1.7-1.9	FORTEAU FORMATION LIMESTONE	Oölitic CALCITE 98% QUARTZ 2%		6.4	5.8	138 (20000)	11.2	0.35
A7/24	2.28-2.35	FORTEAU FORMATION LIMESTONE		2.717					
A8/28	2.65-2.8	FORTEAU FORMATION LIMESTONE	Oölitic (Same as #21)		3.1	50.7	145 (21080)	9.5	0.31
A9/30	1.69-1.74	HAWKE BAY FORMATION SANDSTONE	QUARTZ 75% CALCITE 20% FELDSPAR 5%	2.781	66.9	54.3	215 (31110)	6.4	0.21
A10/34	1.94-2.06	HAWKE BAY FORMATION SANDSTONE	QUARTZ 98% FELDSPAR 2% CALCITE <1%		95.1	55.1	238 (34440)	9.6	0.16
A11/37	2.14-2.19	HAWKE BAY FORMATION SANDSTONE		2.659					
A12/39	1.85-1.9	HAWKE BAY FORMATION DOLOMITE	DOLOMITE 98% QUARTZ 2%		4.0	53.3	244 (35400)	89.6	0.31
B1/207	3.17-3.2	FORTEAU FORMATION LIMESTONE		2.69					
B2/206A	2.62-2.81	FORTEAU FORMATION LIMESTONE	CALCITE 95% QUARTZ 5%		6.2	51.3	248 (36000)	10.8	0.27
B3/203	2.1-2.2	FORTEAU FORMATION LIMESTONE	CALCITE 100% QUARTZ <1%		0.9	50.8	176 (25530)	9.3	0.32
B5/200	2.43-2.5	FORTEAU FORMATION LIMESTONE		2.737					

APPENDIX A. (Continued)

POINT LOAD INDEX				ULTRASONIC TESTS	BRAZILIAN SPLIT TEST	PROTODYAKONAV STRENGTH COEFFICIENT
AXIAL MPa		DIAMETRAL MPa		PULSE VELOCITY	TENSILE	
$I_s(60)$	$I_s(50)$	$I_s(60)$	$I_s(50)$	km/s	STRENGTH MPa (PSI)	$f = \frac{20\ n}{l}$
5.5	6.1	3.1	3.5			
					8.6	
				2.68	(1247)	8.1
5.2	5.9		5.4			
4.9	5.4	3.1(?)	3.5(?)			
					8.0	
				4.90	(1160)	
5.8	6.4	6.4	7.1			
>6.4	>7.1	5.0	5.4			
				5.62	11.0	
				5.69	(1595)	
					6.5	
		6.9(?)	7.8(?)	3.57	(943)	10.7
					8.4	
				2.97	(1233)	4.8
>6.4	>7.1	2.1	2.1			
						12.0
4.9	5.4	3.8	4.1			
2.3	2.7	5.0	5.4			
3.8(?)	4.1					
				5.25	12.8	
					(1856)	
				5.66	5.4	8.3
					(783)	
5.0	5.4	4.2	4.8			

APPENDIX B. Summary of soil tests from seabed samples obtained during the 1981 offshore borehole program (adapted from SNC–Lavalin, 1982b)

BH No. / TP. No.	SA No.	DEPTH (m)	FINAL DESCRIPTION (LAB. TESTS) (GRAIN SIZE ANALYSES)	RELATIVE DENSITY (SG)	WATER % CONTENT	UNIT WEIGHT Kg/m³	° (DEGS)
A1-11	BAG	GRAB. WITH SHELLS	SANDY GRAVEL	2.70/ 2.75	6.2	2002	37/ 37
A2/14	1	1.2-1.3	SILTY SAND SOME GRAVEL (TILL)	2.71	19.2		41
	4	1.3-1.5	SILTY SAND & GRAVEL TILL				
	5	1.5-1.66	SILTY SAND & GRAVEL TILL				
	6	1.66-1.84	SILTY GRAVELLY SAND (TILL)				
A4/7C	1C	1.19-1.35	SANDY GRAVEL TRACE SILT	2.80	1.3		38
	1D	1.19-1.35 (IN TUBE)	SILTY GRAVELLY SAND TILL	2.73	6.4	2280 2360 2340	
A5/20	1	1.21-1.35 1.31-1.43	SAND & GRAVEL TR. SILT	2.71	12.3		42
	8	1.9-2.1	SILTY GRAVELLY SAND (TILL)	2.72	6.8	2370 2350 2360	
A10/34/ 34A	1	1.16-1.34	SAND & GRAVEL TR. SILT	2.76	11.2		37
A11/37	1	1.16-1.34	GRAVELLY SAND SOME SILT				
	4	1.77-1.86	SANDY GRAVEL SOME SILT (TILL)	2.77	10.8		
	5	1.86-2.05	SANDY GRAVEL SOME SILT (TILL)	2.74	7.9	2390 2380	
B1/207	1	1.15-1.33	GRAVELLY SAND SOME SILT (TILL)	2.74	12.2		40
B1/207		1.52-1.68	SILTY SAND & GRAVEL TILL	2.70		2534	
B3/203	BAG	ANCHOR SAMPLE	SILT & CLAY TR. SAND	2.83	57.8		
B4/202A	1	1.14-1.33	SAND, TRACES OF GRAVEL & SILT	2.71	32.2		41

APPENDIX B. (Continued)

DIRECT SHEAR TEST			ATTERBERG LIMITS	S_s MIN VANE (REM)	TRIAXIAL TEST				
CU. (kPa)	VOID RATIO (AVERAGE) (UNIT WEIGHT) (kg/m³)	POROSITY (AVERAGE) %	LL/PL/PI	kPa	° (DEG.)	C' (kPa)	TOTAL UNIT WT (KNM³)	WATER CONTENT %	S_s (kPa)
25/	1.64	62.1/							
11	(1025)/	51.9							
	1.08								
	(1240)								
	0.66								
7	(1630)	39.8							
	0.84								
7	(1500)	45.6							
					39.8 TO	0 TO	22.8	6.36	480
					40.5	30	23.6	6.36	585
							23.4	6.33	989
	0.69	40.8							
10	(1590)								
							23.7	6.01	617
					40.5	0 TO	23.5	6.32	848
					44.0	30	23.6	7.23	1089
	1.13								
16	(1340)	53.0							
					35.8 TO	0 TO	23.9	8.16	600
					39.0	50	23.8	7.93	660
							23.9	7.93	394
	0.91								
0	(1500)	47.6							
			15		42			4.8	830
			12		28	0	24.8	4.7	457
			47	2.8					
			24	2.4					
			23	2.7					
15	1.21								
	(1230)	54.8							

MAPS
NOT
FILMED

CARTES
OMISES